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Solar energy in the United Arab Emirates: A review

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ABSTRACT

The primary goal of this work is to assess the potential of solar energy as an essential future energy source in the oil-rich United Arab Emirates. The findings of this study are based on the national energy production and consumption portfolios, detailed quantitative analysis of the solar energy resource, the local operating conditions of solar installations and the current status of technology. This study also offers an extensive literature review on the development of solar energy in the UAE to investigate: (i) methods for evaluating the solar resource, (ii) the effect of the local environmental operating conditions on the performance of different technologies, (iii) strategies for financing projects and encouraging home-owners to install PV, (iv) and benefits of solar energy to the electricity generation, water production and transportation sectors.

Contents

Abbreviations: CPV, concentrated PV; CSP, concentrated solar power; DHI, diffuse horizontal irradiance; DNI, direct normal irradiance; GHI, global horizontal irradiance; PV, photovoltaics; UAE, United Arab Emirates

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1. Introduction

The United Arab Emirates (UAE) is known for its large oil and gas reserves, but since 2006, it has been involved in various unprecedented activities in the renewable energy sector. This makes it an odd case in the renewable energy map, which has been dominated by countries with a completely different energy portfolio. Those activities are driven by: a rapidly increasing energy and water demand as a consequence to a rapid population growth and economic development, desire to maintain a strong position in the world energy market, necessity to diversify an oil-based economy, and a sense of moral responsibility towards the planet. In addition to these drivers, a good exposure to the sun justifies why solar energy has dominated those activities [1].

The aim of this research is to review and build on the existing knowledge to assess whether solar energy can be an essential part of the UAE's energy mix. If yes, what benefits and challenges are associated with a wide implementation of solar energy projects locally? It is worth noticing that the UAE has very similar political, socio-economic and environmental characteristics as the Gulf Co-operation Countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia in addition to the UAE). Therefore, the findings reported here may apply to these countries as well.

We present this research work in five parts. First, we provide an overview of the current energy and emissions portfolios of the country. In a second part, we assess the solar energy resource by reporting results from different studies, and presenting our own estimations. This will enable us compare solar energy exposure in the UAE with emerging solar markets around the globe. This part of the study also discusses the various approaches that have been used for assessing the solar energy resource in the UAE. In a third part, we will discuss the environmental operating conditions of solar installations and how that affects the performance of various technologies. The forth part reviews solar energy projects and programs within the UAE borders, as well as those implemented abroad and involve UAE entities. In a forth part, benefits of solar energy to the transportation, water production, and electricity production sectors are discussed. In the last part, we discuss how policies can play a role towards a wide adoption of solar energy in the UAE.

2. Energy portfolio

The UAE consists of seven emirates, and each emirate is equivalent to a principality with its own government. The seven emirates are: Abu Dhabi being the largest Emirate and also the capital, Ajman, Dubai, Fujairah, Ras-Al-Khaimah, Sharjah and Umm Al-Quwain. The country shares borders with Oman and Saudi Arabia, it has a 650 km long coast and a surface area of 83,600 km^2.

In this section, we review the energy and electricity sectors. We also look at the sources of green house emissions in these sectors.

2.1. Primary energy production and consumption

Currently, the two main sources of energy in the UAE are oil and natural gas, while other sources such as coal and solar energy contribute marginally (less than 0.1%) towards meeting the ever increasing demand [2]. As of 2011, energy consumed was 87.2 million tones oil equivalent (1,014,136 GWh), among which, 35% came from burning oil and the remaining 65% from natural gas (Fig. 1) [2–4]. Another interesting observation is that the share of gas and oil in the energy mix for local production has not changed significantly in the period of 2001–2011, while total energy consumption multiplied by 1.66 (5.2% increase per year) (Fig. 1). If this trend continues, energy consumption would double every 13.7 years.

The UAE currently has the world's 8th largest reserve of oil, which represents 5.9% of the world's reserve [2]. This is expected to be totally consumed in the next 80.7 years if production remains at 2011 levels [2,4]. In addition, as of 2011, the UAE produced 3.32 million barrels per day, which represents 3.8% of oil produced worldwide. This high consumption is associated with high local consumption. Although the population of the UAE is around 0.1% of the world's population, 0.8% of oil produced worldwide was consumed in the UAE in 2011 [2–4].

In Fig. 2, we show the amount of oil produced and consumed in the UAE in the period 2001–2011 [3]. We see that oil production has been sensitive to the international oil markets, while consumption has been consistently increasing except for the year 2009 when it decreased then resumed its usual trend. These production fluctuations would affect the GDP of oil-based economies such as the UAE.

In Fig. 3, we show how oil produced is used by using data reported on the year 2009. From both figures (Figs. 2 and 3), we see that around 80% of oil produced is exported, and around 8% only is consumed locally [2,5].

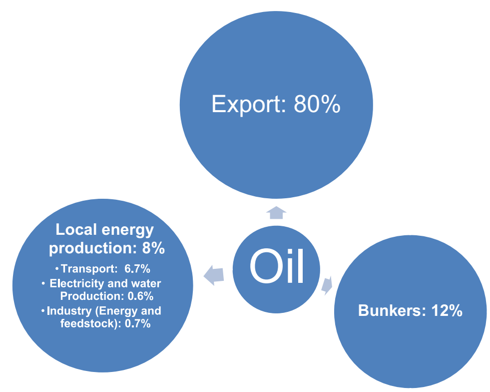

Fig. 3. Breakdown of oil production and consumption in the UAE in 2009 [3,5].

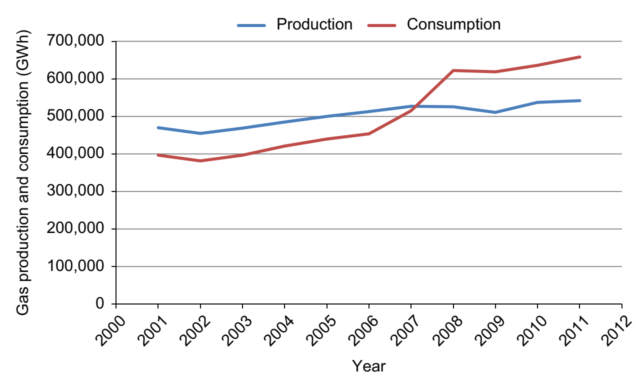

Fig. 4. Natural gas production and consumption in the UAE [3].

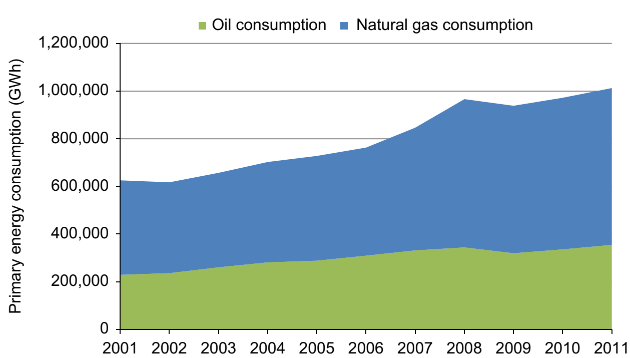

Fig. 1. Sources of energy production in the UAE [3].

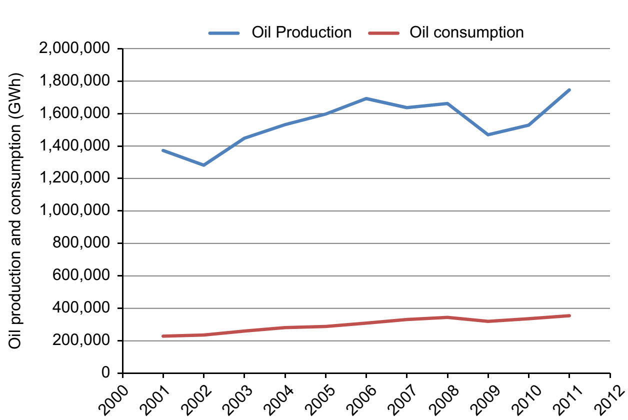

Fig. 2. Oil production and consumption in the UAE [3].

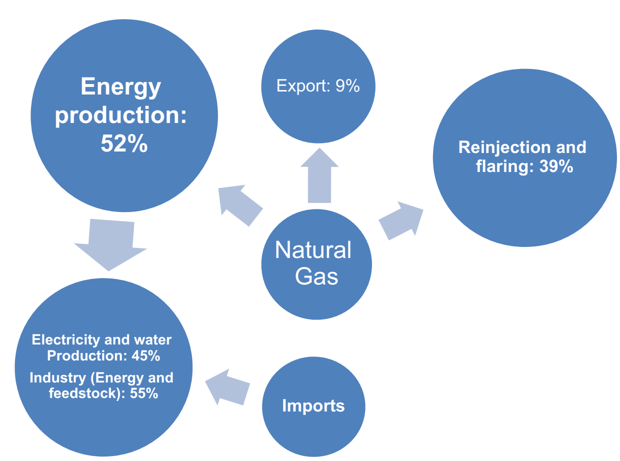

Fig. 5. Breakdown of gas production and consumption in the UAE in 2009 [3,5].

The UAE has also the world′s 7th largest reserve of natural gas, which represents 2.9% of the world′s proven reserve [2,4]. However, because of high energy consumption, and a gradual shift towards gas-based power generation capacity, the UAE has become a net importer of this substance since 2007 (Fig. 4) [2–4]. To meet local demand, 62% of gas produced locally is used in addition to the imports (Fig. 5) [2,5]. It is worth noticing that 45% of gas consumed locally is used for electricity and water production, while 55% is consumed in the industrial sector (Fig. 5).

2.2. Electricity production and consumption

There are four utility companies in the UAE [6]: Abu Dhabi Water and Electricity Authority (ADWEA), Sharjah Elecricity and Water Authority (SEWA), Dubai Water and Electricity Authority (DEWA), and the Federal Electricity and Water Authority (FEWA). Fig. 6 shows their production capacity between 2006 and 2011 [6]. We see that ADWEA′s contribution to the total generation capacity is around 50%, and that of DEWA is around 30%, while SEWA and FEWA combined contribute by around 20%. This can be explained by the relatively high population, and high commercial and industrial activity in the emirates of Abu Dhabi and Dubai. Also, ADWEA exports electricity to other emirates to meet demand.

These four utility companies operate to meet a demand that is growing at the same rate as population growth: while population growth recorded between 2006 and 2011 is 11% per annum (see Fig. 7) [7], electricity demand was growing by 10.8% per annum (see Fig. 8) [8]. This figure is also driven by high per capita consumption of electricity and water. For instance, the UAE is the 10th world largest consumer of electricity per capita [8]. To put this in perspective, the world electricity consumption was increasing by 3.7% per year during the same period of time, and the world's population was also growing at a similar rate [8].

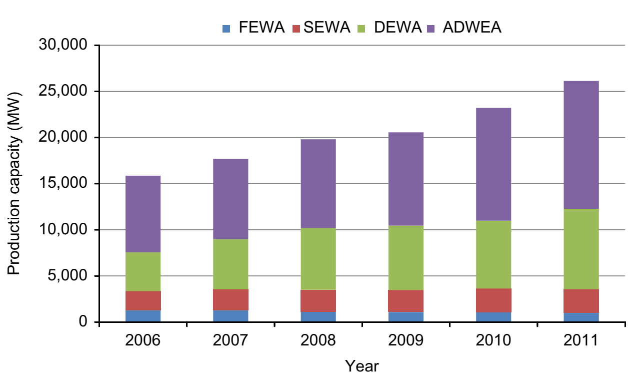

Fig. 6. Electricity production and consumption in the period 2006–2011 [6].

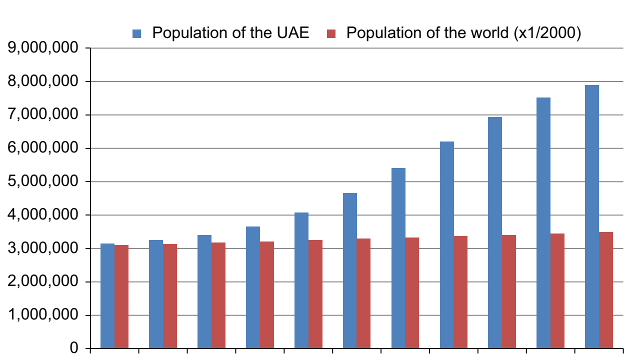

Fig. 7. Population growth in UAE and the world [7].

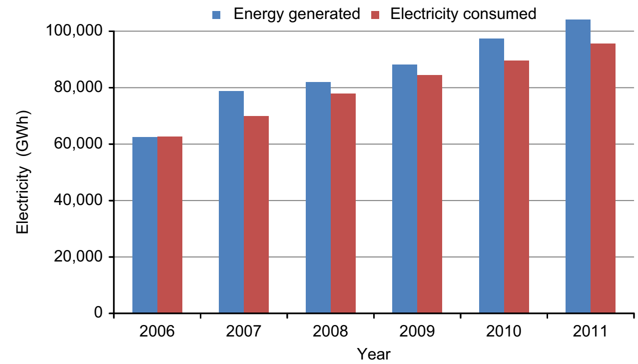

Fig. 8. Electricity production and consumption in the period 2006–2011 [6].

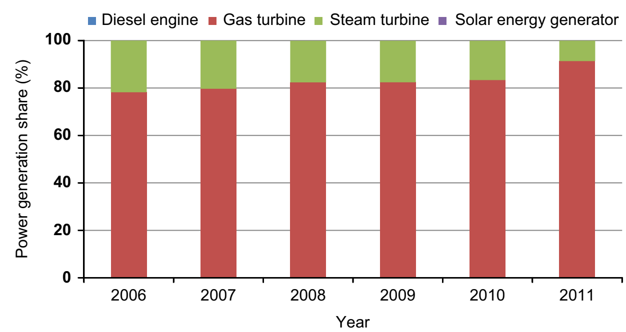

Fig. 9. Sources of electricity production in the period 2006–2011 [6].

From Fig. 8, we can estimate a 4.3–11.3% of deficiency between electricity produced and generated. This could be indicative to losses in the production and distribution network.

Utility companies use mainly two types of generators: gas turbines and steam turbines and rely almost exclusively on natural gas to run their generators. The generation capacities of each utility tend to have different characteristics, and they also tend to change by time. For instance, while FEWA's generation capacity has been 91–100% based on gas turbines between 2006 and 2011, DEWA's generation capacity has been 72–96% based on gas turbines. ADWEA and SEWA were 78–89% and 79–83% based on gas turbines, respectively. The rest of the capacity for all the utilities is based on steam turbines, except SEWA which has 14–19 MW of diesel engine generation capacity, and ADWEA which operates around 112 MW of solar capacity. Although these numbers show that the power generation source in the UAE varies from one utility company to another, overall, 4/5 of the total generation capacity has been based on gas turbines and 1/5 on steam turbines (see Fig. 9). This could be due to the short starting time (i.e. quick response) of the gas turbine technology. In addition, paying close attention to Fig. 9 reveals a consistent shift towards increasing gas turbine generation and decreasing steam turbine generation. Another important observation is that electricity production relies on natural gas, and the UAE has been a net importer of this commodity since 2007.

With regard to electricity consumption, 34–37% has been consumed in the residential sector, 30–37% by the commercial sector, 7–12% by the industrial sector, and the rest 19–27% has been used in other applications (Fig. 10). For the period between 2006 and 2010, we noticed that electricity consumption in the residential sector has increased from 34% to 37%, and consumption in the commercial sector has also increased from 30% to 37%, while consumption in the industrial sector has dropped from 9% to 7%. These trends show that consumption has been driven by the increasing population and commercial activity, which accounted

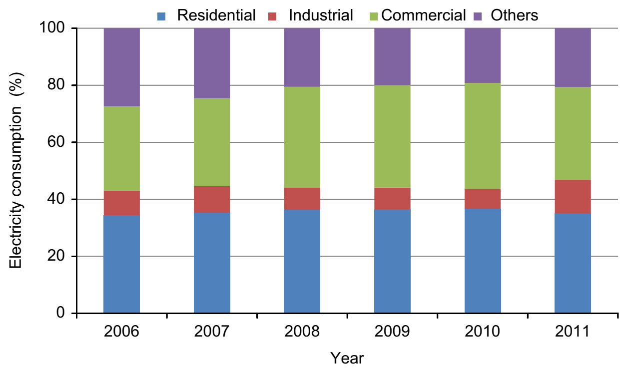

Fig. 10. Electricity consumption by sector in the period 2006–2011 [6].

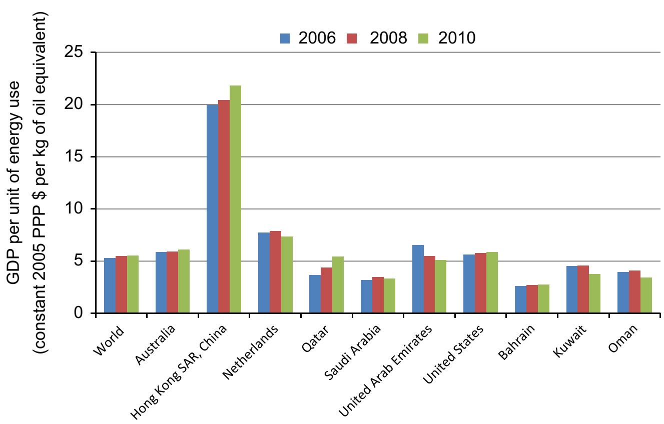

Fig. 11. GDP per unit of energy use in the UAE and countries with similar characteristics [3].

for more than 76% of the total. However, in 2011, this trend has been interrupted by a jump from 7% to 12% in the industrial sector, which still left the commercial and residential sectors with a 68% share of the total consumption (Fig. 10). This means that the largest share of produced electricity is consumed in buildings. Later in this research, we will show that this high electricity consumption in buildings is associated with the high cooling load required to achieve thermal comfort in one of the hottest regions in the world.

2.3. Primary energy and electricity consumption per capita

While energy and electricity demand are driven by a continuously growing population, we acknowledge that it also depends on the per capita consumption which varies for reasons beyond the scope of this work.

It has been suggested in several studies that there is a strong correlation between the GDP per capita and energy consumption per capita and electricity consumption per capita [9–11]. Therefore, in order to assess energy and electricity consumption per capita in the UAE, we compare those figures with those recorded in countries with a similar GDP per capita as the UAE (47,893 USD in 2011): Hong Kong (50,551 USD), United States (48,112 USD), Netherlands (42,779 USD) and Australia (42,779 USD) [3]. In Fig. 11, we plotted GDP per energy use for these countries, and we found that all countries have a similar ratio except for Hong Kong, which corroborates the claim above.

Also, for a better assessment, we include the members of the Gulf Co-operation Council because they have similar socio-economic characteristics: Bahrain, Kuwait, Saudi Arabia, Oman and Qatar. We also include the world's average as a reference.

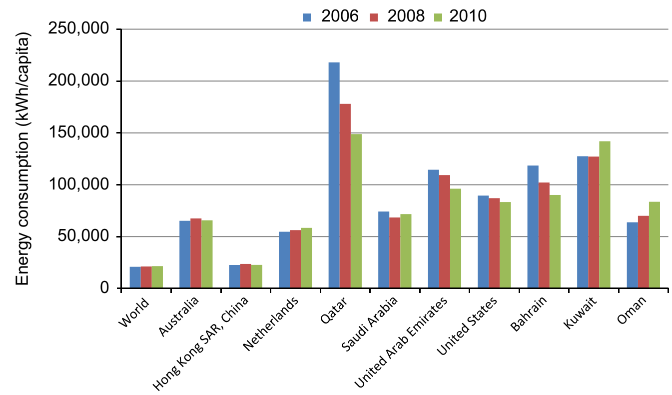

Fig. 12. Energy consumption per capita in the UAE and countries with similar characteristics [3].

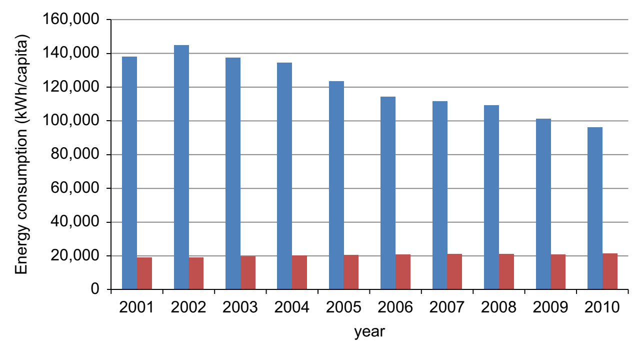

Fig. 13. Energy consumption per capita in the UAE and the world [3].

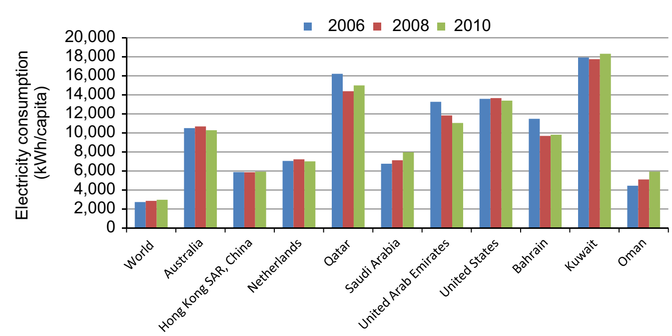

Fig. 14. Electricity consumption per capita in UAE and countries with similar characteristics [3].

We limit our assessment to the past recent years: 2006, 2008 and 2010.

In the years 2006, 2008 and 2010, the UAE was ranked 7th, 7th then 8th world's largest energy consumer per capita, respectively. Among the 10 countries with similar characteristics listed above (see Fig. 12), the UAE ranks 4th in 2006, and 3rd in 2008 and 2010; and when compared with the world's average, the UAE consumption per capita has been 5–6 fold (see Fig. 12). These figures reflect very high energy consumption per capita in the UAE. However, data of the years 2001 through 2010 show an average yearly decrease in the UAE consumption of 3.9% per annum in parallel with a world's average increase of 1.4% per annum (see Fig. 13) [3].

In all years 2006, 2008 and 2010, the UAE maintained the 12th position of world's largest electricity consumer per capita. Among the 10 countries with similar characteristics listed above (see

Fig. 12), the UAE ranks 4th in 2006, 2008 and 2010; and it was 4.5 times the world's average (see Fig. 14). These figures reflect very high electricity consumption per capita. However, data of the years 2001 through 2010 show a consistent yearly decrease in the UAE consumption of 4.4% per year since 2005 till 2010, in parallel with a world's average increase of 2.2% per annum, during the same 5-year period (see Fig. 15).

2.4. Green house gas (GHG) emissions

As a result to a fossil fuel based energy generation capacity, the UAE has a high ecological footprint per capita, and it actually had the world's highest in 2010. In the years 2006, 2008 and 2010, the UAE was ranked 4th, 6th then 1st world's largest CO_2 emitter per capita, respectively [3,12]. Among the 10 countries with similar characteristics, the UAE ranked 3rd in 2005, 2007 and 2009 (see Fig. 16) [3]. Those figures reflect a very high CO_2 emission rate per capita, which is actually the result of high energy consumption per capita, and a 100% fossil fuel based energy generation capacity. For

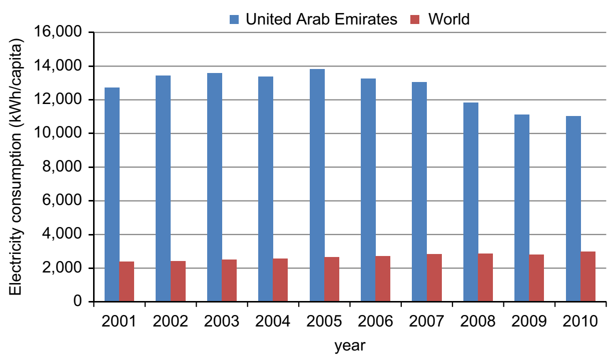

Fig. 15. Electricity consumption per capita in UAE and the world [3].

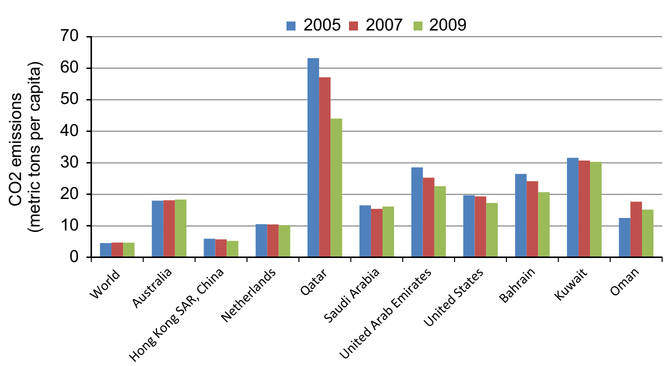

Fig. 16. CO_2 emission in UAE and countries with similar characteristics [3].

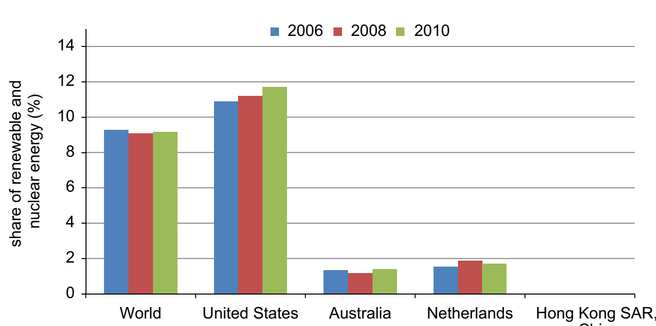

Fig. 17. Share of renewable and nuclear energy and countries with similar characteristics [3].

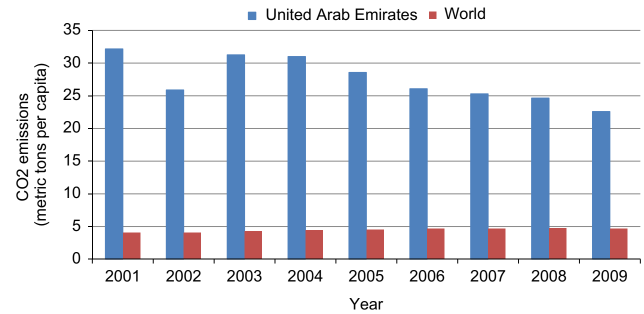

Fig. 18. CO_2 emission in the UAE and the world [3].

instance, the United States, Australia and Netherlands had less footprint per capita; and this could be attributed partly to a small renewable energy share in their energy mix (see Fig. 17). However, as it could be inferred from Figs. 13 and 15, data of the years 2001 through 2009 show a consistent yearly decrease in the UAE CO_2 emissions per capita of 5.2% per annum since 2003 till 2009, in parallel with a world's average increase of 1.5% per annum, during the same 6-year period (see Fig. 18).

In 2013, the UAE's Environment Agency published a study that estimates GHG emissions from all sectors in the Emirate of Abu Dhabi, which is the largest energy producer and consumer [13]. The study showed that, in 2010, electricity and water production were responsible for around 1/3 of all GHG emissions. The second largest contributor was emissions from vehicles on the roads by around 12% (see Fig. 19) [13]. Oil and gas processing, and metallurgical industry came third by 17% share each. The study also went into identifying 10 activities that cumulatively produced 95% of the 99,101 Gg CO_2 equivalent emitted in 2010, and it was found that half of total emissions came from stationary combustion, and 11.7% from road vehicles (see Fig. 20) [13].

2.5. Analysis

From the above overview, we learn that the current UAE energy mix is based exclusively on oil and gas with a minor contribution from other resources. This dictates a transition towards a more sustainable energy mix for a more sustainable economic development. We have shown that the UAE is already a net importer of gas since 2007, and that its oil reserves may last for 80.7 years if production levels remain constant. We have also calculated a 13.7 years cycle for doubling in energy consumption. These facts emphasize the necessity of alternative energy sources such as solar in order to sustain economic development in the short, medium and long terms.

We have also seen that oil production capacity has been sensitive to the unstable international oil market. Such fluctuations in production may have negative effects on the local economy. As a matter of fact, several studies suggest a strong correlation between the world energy market and GDP [9–11]. Therefore, in order to maintain a stable share in the world energy market, investment in alternative energy sources whose prices are insensitive to geo-political events is rather necessary.

Another characteristic of the local energy market is a rapidly increasing consumption. If we consider the fact that the price of oil and gas in the local market is lower than in the international market, it becomes clear that reductions in local demand, or meeting part of that demand by using alternative energy sources at a lower cost could be associated with significant economic benefits.

With regard to electricity production, 80% of supply is provided by two electric utility companies to meet a demand that increases at the same rate with population growth (11% per annum).

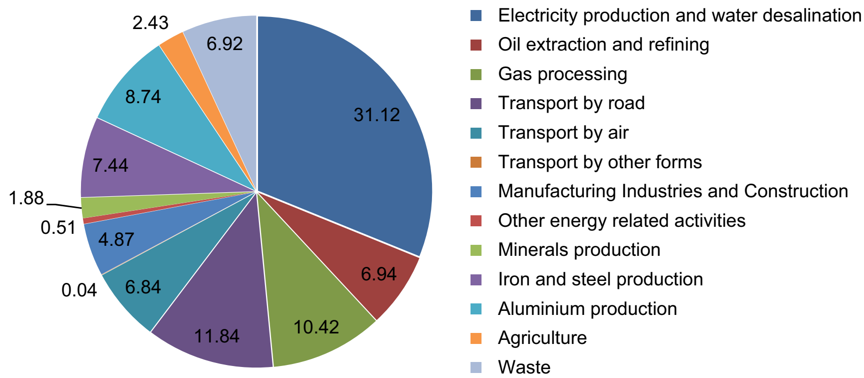

Fig. 19. Sources of CO_2 emissions in the emirate of Abu Dhabi [13].

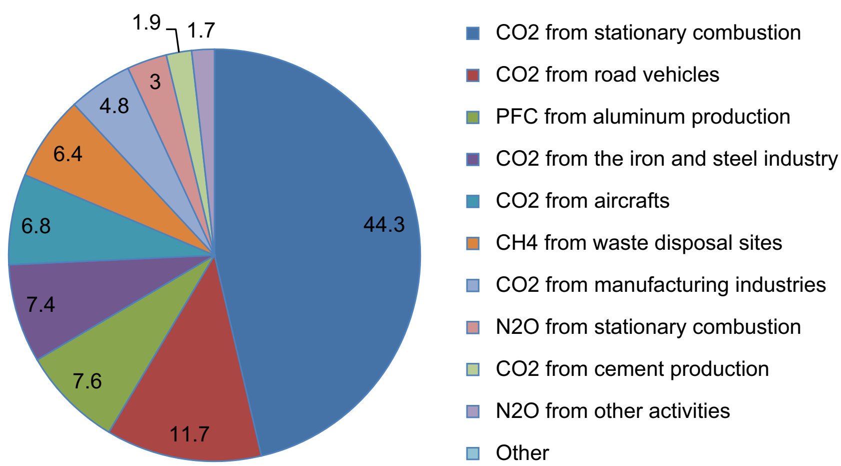

Fig. 20. The 10 sectors responsible for 95% of GHG emissions in Abu Dhabi in 2010 [13].

This suggests that any supply measures implemented by these two utilities would affect the national electricity (and water) market directly, and significantly.

With regard to electricity consumption, we observed that 68–76% of electricity is consumed in buildings: residential and commercial sectors. This fact favors the usage of building integrated power generators such as building integrated PV and rooftop PV. We have also observed that up to 11.3% of electricity produced per year is not used. This could be attributed to transportation and distribution losses. Therefore, distributed generators of electricity may contribute towards decreasing these losses.

We have also seen that energy consumption is increasing rapidly (and GHG emissions therefore), and we could identify the factors contributing to this: (1) a significant part of electricity consumed in buildings is used for cooling/air conditioning because of the local humid and hot climate, and this correlates directly with the local population growth, which is driven partly by a high influx of expatriates (Emiratis represent 15% only of the population); (2) a fast growing population that determines the rate at which electricity consumption grows; (3) emergence of new energy intensive industries (e.g. aluminum production); (4) energy prices that are very low for a high income society; and (5) dominance of individual transportation.

When compared with other countries, we observed that the UAE is one of the highest energy consumers per capita, and it ranked 4th among 10 countries with similar characteristics. Relatively lower energy consumption levels in those 10 countries could be regarded as achievable sustainability targets for the UAE. This relatively high energy consumption per capita also highlights the potential of energy efficiency towards a more sustainable energy transition. However, we have observed that, while energy consumption per capita has been increasing on average worldwide, it has been decreasing in the UAE. This would slow the rapid increase of the country's energy demand.

The figures above also suggest that the UAE is one of the highest electricity consumers per capita, and it ranked 4th among 10 countries with similar characteristics. This again highlights the potential of energy efficiency towards a more sustainable energy mix, especially that 68–76% of electricity is being consumed in buildings. However, while energy consumption per capita has been increasing on average worldwide, it has been decreasing in the UAE. This would slow the rapid increase of the country's electricity demand.

With regard to GHG emissions, we saw that the UAE had the 3rd highest CO_2 footprint per capita among the 10 countries with similar characteristics. Similarly to electricity and energy consumption, while the per capita footprint has been increasing on average worldwide, it has been decreasing in the UAE. We have also concluded that the main source of emissions was in the water and electricity production sector (1/3 in the emirate of Abu Dhabi). When different activities were studied separately, it was revealed that almost half of all emissions come from stationary combustion in the emirate of Abu Dhabi. Transportation by road has also had a significant contribution to GHG emissions. Therefore, more sustainable practices in the transportation, water and electricity production sectors would reduce the GHG emissions significantly.

After reviewing the energy sector in the UAE, we intend to study how solar energy would contribute towards tackling the issues above: diversifying the sources of energy, meeting local

Table 1
Comparison between the different methods used for estimating global solar irradiation parameters in the United Arab Emirates.

Technique	Location	RMSE	MBE	Comment	Reference
Artificial neural networks	Al-Ain City	0.276	0.00009	Input parameters are sunshine duration, temperature, wind speed and humidity recorded between 1995 and 2006. Method used is multilayer perceptron (MLP).	[25]
Artificial neural networks	Al-Ain City	0.287	0.00054	Input parameters are sunshine duration, temperature and wind speed measured between 1995 and 2006. Method used is multilayer perceptron (MLP).	[25]
Artificial neural networks	Al-Ain City	0.391	−0.00012	Input parameters are sunshine duration, temperature and humidity measured between 1995 and 2006. Method used is multilayer perceptron (MLP).	[25]
Artificial neural networks	Al-Ain City	0.374	0.00062	Input parameters are sunshine duration, wind speed and humidity measured between 1995 and 2006. Method used is multilayer perceptron (MLP).	[25]
Artificial neural networks	Al-Ain City	0.318	−0.00034	Input parameters are temperature, wind speed and humidity measured between 1995 and 2006. Method used is multilayer perceptron (MLP).	[25]
Artificial neural networks	Dubai City	0.269	−0.00255	Input parameters are sunshine duration, temperature, wind speed and humidity between 2002 and 2008. Method used is multilayer perceptron (MLP).	[26]
Artificial neural networks	Dubai City	0.299	0.00043	Input parameters are sunshine duration, temperature and wind speed measured between 2002 and 2008. Method used is multilayer perceptron (MLP).	[26]
Artificial neural networks	Dubai City	0.637	−0.00029	Input parameters are temperature, wind speed and humidity measured between 2002 and 2008. Method used is multilayer perceptron (MLP).	[26]
Artificial neural networks	Dubai City	0.221	0.04826	Input parameters are sunshine duration, temperature and humidity measured between 2002 and 2008. Method used is multilayer perceptron (MLP).	[26]
Artificial neural networks	Dubai City	0.280	0.00610	Input parameters are sunshine duration, wind speed and humidity measured between 2002 and 2008. Method used is multilayer perceptron (MLP).	[26]
Artificial neural networks	Dubai City	0.319	0.00025	Input parameters are sunshine duration, temperature, wind speed and humidity between 2002 and 2008. Method used is radial basis functions (RBF).	[26]
Artificial neural networks	Dubai City	0.319	−0.00001	Input parameters are sunshine duration, temperature and wind speed measured between 2002 and 2008. Method used is radial basis functions (RBF).	[26]
Artificial neural networks	Dubai City	0.681	−0.00061	Input parameters are temperature, wind speed and humidity measured between 2002 and 2008. Method used is radial basis functions (RBF).	[26]
Artificial neural networks	Dubai City	0.319	−0.00003	Input parameters are sunshine duration, temperature and humidity measured between 2002 and 2008. Method used is radial basis functions (RBF).	[26]
Artificial neural networks	Dubai City	0.340	0.00909	Input parameters are sunshine duration, wind speed and humidity measured between 2002 and 2008. Method used is radial basis functions (RBF).	[26]
Artificial neural networks	Abu Dhabi City	0.133	−0.00350	Input parameter is sunshine duration only which was measured between 1995 and 2007. A linear regression model is used.	[27]
Artificial neural networks	Abu Dhabi City	0.153	0.00940	Input parameter is sunshine duration only which was measured between 1995 and 2007. A quadratic regression model is used.	[27]
Artificial neural networks	Abu Dhabi City	0.132	0.00060	Input parameter is sunshine duration only which was measured between 1995 and 2007. A cubic regression model is used.	[27]
Artificial neural networks	Abu Dhabi City	0.174	0.03700	Input parameter is sunshine duration only which was measured between 1995 and 2007. An exponential regression model is used.	[27]
Artificial neural networks	Abu Dhabi City	0.178	0.01480	Input parameter is sunshine duration only which was measured between 1995 and 2007. A logarithmic regression model is used.	[27]
Artificial neural networks	Abu Dhabi City	0.214	0.01510	Input parameter is sunshine duration only which was measured between 1995 and 2007. A linear-logarithmic regression model is used.	[27]
Artificial neural networks	Abu Dhabi City	0.182	0.00770	Input parameter is sunshine duration only which was measured between 1995 and 2007. An exponential-quadratic regression model is used.	[27]
Artificial neural networks	Al-Ain City	0.217	−0.13410	Input parameter is sunshine duration only which was measured between 1995 and 2007. A linear regression model is used.	[27]
Artificial neural networks	Al-Ain City	0.213	−0.00680	Input parameter is sunshine duration only which was measured between 1995 and 2007. A quadratic regression model is used.	[27]
Artificial neural networks	Al-Ain City	0.208	0.00160	Input parameter is sunshine duration only which was measured between 1995 and 2007. A cubic regression model is used.	[27]
Artificial neural networks	Al-Ain City	0.259	0.00530	Input parameter is sunshine duration only which was measured between 1995 and 2007. An exponential regression model is used.	[27]
Artificial neural networks	Al-Ain City	0.233	0.10400	Input parameter is sunshine duration only which was measured between 1995 and 2007. A logarithmic regression model is used.	[27]
Artificial neural networks	Al-Ain City	0.210	−0.00590	Input parameter is sunshine duration only which was measured between 1995 and 2007. A linear-logarithmic regression model is used.	[27]
Artificial neural networks	Al-Ain City	0.368	0.26580	Input parameter is sunshine duration only which was measured between 1995 and 2007. An exponential-quadratic regression model is used.	[27]
Artificial neural networks	Five stations in Abu Dhabi emirate	0.261	−0.0600	Input parameters are satellite data and sun coordinates: solar zenith angle, solar time, day number, and eccentricity correction. Output parameters are DNI values.	[22]
Artificial neural networks	Five stations in Abu Dhabi emirate	0.256	0.03600	Input parameters are satellite data and sun coordinates: solar zenith angle, solar time, day number, and eccentricity correction. Output parameters are DHI values.	[22]
Artificial neural networks	Five stations in Abu Dhabi emirate	0.124	−0.02900	Input parameters are satellite data and sun coordinates: solar zenith angle, solar time, day number, and eccentricity correction. Output parameters are GHI values.	[22]
Geostatistical analysis	East of Jabal Haffed	0.163	−0.13600	By using the standard Heliostat-2 model.	[21]
Geostatistical analysis	East of Jabal Haffed	0.950	0.00800	By using the DHI-corrected Heliostat-2 model.	[21]
Geostatistical analysis	Al Aradh	0.185	−0.15800	By using the standard Heliostat-2 model.	[21]
Geostatistical analysis	Al Aradh	0.102	−0.01200	By using the DHI-corrected Heliostat-2 model.	[21]
Geostatistical analysis	Al Wagan	0.183	−0.15600	By using the standard Heliostat-2 model.	[21]
Geostatistical analysis	Al Wagan	0.102	−0.01200	By using the DHI-corrected Heliostat-2 model.	[21]
Geostatistical analysis	Madinat Zayed	0.178	−0.15000	By using the standard Heliostat-2 model.	[21]
Geostatistical analysis	Madinat Zayed	0.103	−0.00100	By using the DHI-corrected Heliostat-2 model.	[21]
Analytical and semi-analytical correlations	Abu Dhabi City	0.042	0.03700	Model correlates the monthly average daily global radiation to sunshine hours only.	[32]

Table 1 (*continued*)

Technique	Location	RMSE	MBE	Comment	Reference
Analytical and semi-analytical correlations	Abu Dhabi City	0.123	0.12000	Model correlates the monthly average daily global radiation to sunshine hours only, but by using different correlation factors.	[32]
Analytical and semi-analytical correlations	Abu Dhabi City	0.088	0.08500	Model correlates the monthly average daily global radiation to sunshine hours only, but by using different correlation factors.	[32]
Analytical and semi-analytical correlations	Abu Dhabi City	0.127	0.12500	Model correlates the monthly average daily global radiation to sunshine hours and latitude.	[32]
Analytical and semi-analytical correlations	Abu Dhabi City	0.115	0.11200	Model correlates the monthly average daily global radiation to sunshine hours and ground albedo, cloudless sky albedo and cloud albedo.	[32]
Analytical and semi-analytical correlations	Abu Dhabi City	0.121	0.11700	w Model correlates the monthly average daily global radiation to sunshine hours and water vapor content per unit volume of air.	[32]
Analytical and semi-analytical correlations	Abu Dhabi City	0.062	0.0600	Model estimates the monthly average daily global radiation by using a specific sky model.	[32]
Analytical and semi-analytical correlations	Abu Dhabi City	0.087	0.08500	Model estimates the monthly average daily global radiation by using a different sky model.	[32]
Analytical and semi-analytical correlations	Abu Dhabi City	0.044	0.07100	Model estimates the monthly average daily global radiation by using a different sky model.	[32]
Analytical and semi-analytical correlations	Abu Dhabi City	0.035	0.03000	Model estimates the monthly average daily global radiation by using a different sky model.	[32]
Analytical and semi-analytical correlations	Abu Dhabi City	0.056	0.05300	Model estimates the monthly average daily global radiation by using a different sky model.	[32]
Analytical and semi-analytical correlations	Abu Dhabi City	0.043	0.04000	Model estimates the monthly average daily global radiation by using a different sky model.	[32]

demand, improving income from exports, reducing electricity losses, and reducing GHG emissions in the electricity and water production sectors, and transportation sector. Prior to that, it is mandatory to evaluate the solar energy resource in the UAE, and the operating conditions of different solar technologies in the local environment. Even prior to this, it would make sense to look at the potential of other energy resources that have been evaluated extensively, namely, nuclear and wind.

3. Renewable energy resources

3.1. Wind energy

Several wind speed assessment studies were conducted in different regions in the UAE to see the economic viability of deploying wind turbines. Efforts conducted jointly with DLR in Germany showed moderate values that do not exceed 5 m/s onshore and 7.5 m/s near the shoreline [14], making the UAE wind energy potential the lowest among all GCC countries [15], which can be harnessed at a height of 80 m, to achieve a full load hour of 1176 h per year (i.e. capacity factor of 13.4%). According to Alnaser et al. for wind energy to be economically viable, at least 1400 full load hours (i.e. capacity factor of 16%) are required.

However, a study conducted in Sharjah showed that wind speeds can reach values as high as 13 m/s in some seasons. Janajreh et al. have measured wind speeds in Masdar City (Abu Dhabi) continuously for several months, at different heights between 0 and 50 m. Their conclusion is that the amount of wind in this part of Abu Dhabi is of class 1: poor to fair wind speed [16]. Therefore, wind turbines with a low turning moment and characterized with a low cut-in wind speed can be implemented. In addition to this, it varies significantly during the year [16]. The investigators reveal that they could not go beyond 50 m in height because Masdar City is near the airport, where no structures should exceed 70 m. The authors suggested that wind speeds at higher altitudes should be investigated to know the true potential of wind energy. In a separate study by Janajreh et al. where full year wind assessment was conducted in Masdar City at 50 m, it was reported that 3307 MWh of power can be generated annually, by using a 500 kW wind turbine to achieve a capacity factor of 657 full load hours (i.e. capacity factor of 7.5%) [17]. The same study suggests that a 3.5 kW turbine would achieve 832.2 full load hours (i.e. capacity factor of 9.5%) to generate around 29 MWh annually [17].

The potential of wind was also assessed in the emirate of Fujairah. Based on those analyses, it was announced that a wind generation capacity between 130 MW and 200 MW can be operated [14].

The potential of wind was also assessed in Sir Bani Yas Island (250 km southwest of Abu Dhabi) [14]. A wind turbine of 850 kW was deployed on the island for this purpose. Average wind speeds of 5.1 m/s were measured to achieve 1200–1300 full load hours (i.e. capacity factor of 13.7–14.8%). The system in operation is grid connected, and it generates around 1 GWh of electricity per year, at a cost of 12.5 cents/kWh [14]. Following this demonstration project, a wind generation capacity of 30 MW is envisaged in this location [14].

Shawon et al. have evaluated wind data measured at a height of 10 m in several regions in the GCC including three in the UAE: Al Aradh, Sir Bani Yas and Al Mirfa [18]. The annual average wind speeds reported were 2.35 m/s, 3.86 m/s, and 4.27, respectively, and was classified of class 1: poor to fair wind speed (same conclusion as Janajreh and Taleb [17]). Shawon et al. suggested that these wind speeds would be suitable for water pumping [18].

3.2. Nuclear energy

In December 2009, the Emirates Nuclear Energy Corporation (ENEC) was established to implement the UAE's nuclear energy program, with the objective of meeting 25% of the nation's electricity demand by 2020 [19]. In the same year, the Federal Authority for Nuclear Regulation (FANR) was established to monitor all nuclear-related activities in the country.

The program consists in constructing four plants, with a capacity of 1400 MW each [19]. The first unit is expected to start production in 2017, and all units are expected to be operational by 2020. The Prime contact for constructing the plants was awarded to the Korea Electric Power Corporation (KEPCO), with a value of 20 billion USD, and the location will be Barakah (Southwest of the UAE) [19].

The plants will have a 90% capacity factor, and would generate 44,150 GWh of electricity from 2020 onwards [19]. AlFarra and Abu-Hijleh have conducted a modeling study and showed that electricity can be generated at a low cost of 3.2 cents/kWh, which is low compared with the current cost of 8.15 cents/kWh from natural gas. This takes into account an amortized installation cost of 2.37 cents/kWh, a fixed operating cost of 0.19 cents/kWh, and a fuel cost of 0.64 cents/kWh. The same study also estimated an 83.4% reduction in CO_2 emissions for each 1 kWh of electricity produced [20].

4. Solar energy resource

The UAE lies between 22°30′ and 26°10′ north latitude and between 51^0 and $56^025'$ east longitude which gives an indication of its good solar energy exposure. However, high concentrations of airborne dust particles and high humidity tend to diffuse and attenuate the intensity of solar irradiance. Satellite imaging data and ground measurement data have shown that the magnitude of these effects is seasonal and location dependent [21,23], which makes some solar technologies more suitable than others depending on the location.

The amount of solar energy received in different regions in the UAE has been evaluated in the past by using four approaches: (1) computation based on artificial intelligence techniques (artificial neural networks), (2) ground measurements, (3) processing of satellite imaging data, and (4) analytical or semi-analytical correlations.

4.1. Artificial intelligence techniques (artificial neural networks)

Artificial neural networks is a computation technique which consists in finding the patterns in a known set of input data, and based on these patterns, a set of unknown data can be estimated. This technique has been used extensively in the past to predict solar radiation data in various locations around the world [23]. For the UAE, Assi et al. have used temperature, humidity, wind and sunshine duration measurements recorded between 1995 and 2007 in Al-Ain City (160 km east of Abu Dhabi) to predict the global solar radiation by using artificial neural networks (ANN) [22,25]. Data recorded between 1995 and 2006 were used as input parameters to the model, and data recorded in 2007 were used for testing its accuracy. Five models with different combinations of input data were developed: (1) sunshine duration, temperature, wind speed and humidity; (2) sunshine duration, temperature and wind speed; (3) sunshine duration, temperature and humidity; (4) sunshine duration, wind speed and humidity; and (5) temperature, wind speed and humidity. The models were developed to estimate the monthly average values of global horizontal radiation (GHI). For all models, it was found that the coefficients of determination (R^2) were above 0.87, the root-mean-square error (RMSE) values varied between 0.276 and 0.391 and the mean-bias error (MBE) values ranged between −0.00014 and 0.00009 (see Table 1) [24,25].

Al-Shamisi et al. have used the same technique to estimate global solar radiation in Dubai City by using weather data measured between 2002 and 2010 [24,26]. Data measured during the period 2002–2008 were used as input parameters to the model, and data recorded in 2009 and 2010 were used for testing its accuracy. Like in Assi et al.'s work, Al-Shamisi et al. have developed five models by using the same set of input parameters 1 through 5 mentioned above. However, while Assi et al. have used the multilayer perceptron (MLP) method, in this study, all five models were developed by using two different methods called: the multilayer perceptron (MLP) method and the radial basis functions (RBF) method. The first one had led to better results with coefficients of determination (R^2) above 0.86, root-mean-square error (RMSE) values between 0.221 and 0.637, and mean-bias error (MBE) values between −0.00255 and 0.04826 (see Table 1). The coefficients of determination (R^2) obtained by using the second method (RBF) were above 0.84, and the calculated root-mean-square error (RMSE) values and mean-bias error (MBE) values were in the range 0.319–0.681 and −0.00001 to 0.00909, respectively (see Table 1) [24,26].

In another work, Assi et al. have used this technique for estimating global solar radiation in Abu Dhabi City and Al-Ain City, but by using the sunshine duration measurements taken between 1995 and 2007 as the only input parameters [24,27]. In this work, Assi et al. used several mathematical correlations: linear, quadratic, third order, logarithmic, linear-logarithmic, exponential and exponential-quadratic. For the case of Abu Dhabi City, the highest coefficient of determination was 94%, and it was obtained by using the linear correlation, while for Al-Ain City, the highest coefficient of determination was 84%, and it was obtained by using the logarithmic correlation (see Table 1) [27]. The root-mean-square error (RMSE) values and mean-bias error (MBE) values obtained are shown in Table 1.

Instead of using ground data, Eissa et al. have used satellite data to estimate solar radiation (DNI, DHI and GHI) across the UAE at 15 min and 3 km resolutions [22]. One ANN model was developed for estimating DHI, and another one for estimating the optical depth of the atmosphere. Output parameters from both models were used to obtain DNI and GHI. Ground measurements data of the full year of 2010 recorded in three weather stations were also used as input parameters, and data of the year 2009 recorded in two other weather stations were used to test the accuracy of the models. The RMSE values obtained for DNI, DHI and GHI were 0.261, 0.256 and 0.124, respectively. The MBE values obtained were −0.06, 0.036 and −0.029 [22].

4.2. Remote sensing techniques by processing satellite data

Since its establishment in 2012, the Research Center for Renewable Energy Mapping and Assessment at Masdar Institute in Abu Dhabi have conducted several research projects to use satellite imaging data to assess the solar energy resource in the UAE [28]. Some of the efforts have focused on studying the characteristics of the atmosphere such as humidity and airborne dust particles, and their effect on the incident solar radiation. Those studies resulted in the UAE's solar energy atlas maps, which are shown in Figs. 21 and 22 for the yearly GHI and DNI, and Figs. 23–26 for the monthly GHI and DNI [29].

Eissa et al. have used this technique to compute global horizontal radiation values in seven regions across the UAE [21]. The model Heliosat-2 was used, and the input parameters were the monthly Linke turpidity factor normalized to Air Mass 2 (AM2) and cloud index. Those were obtained from seven weather stations

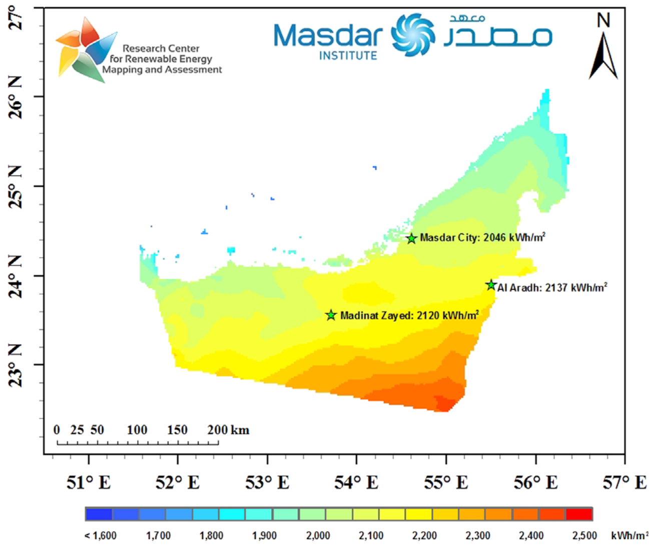

Fig. 21. Yearly GHI map obtained by processing satellite and ground measurement data [29].

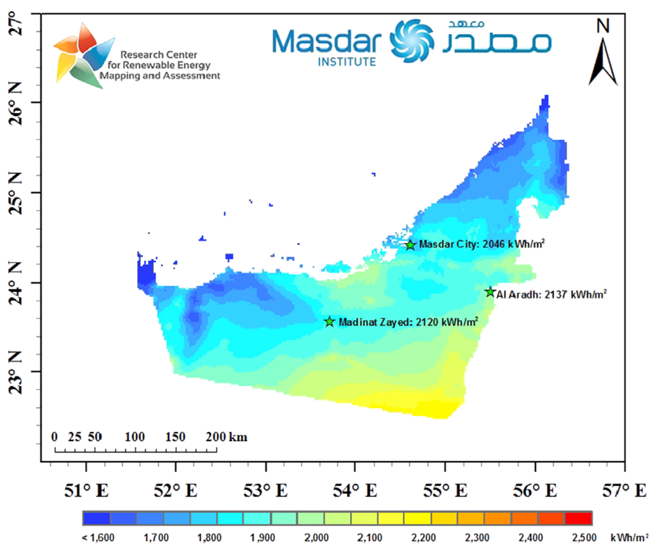

Fig. 22. Yearly DNI map obtained by processing satellite and ground measurement data [29].

in the UAE and the satellite Meteosat, respectively. The Linke turpidity factor normalized to AM2 was used for estimating clear sky global horizontal irradiance (GHI) and direct normal irradiance (DNI) values, and the irradiance measured onboard of the satellite was used for determining the cloud index, which ultimately enabled the estimation of GHI. The authors mentioned that they were unable to process the satellite data for regions near the cost, and therefore they discarded the three near coastal regions from their study [21].

For verifying the model, GHI, DNI and direct horizontal irradiance (DHI) values recorded in the ground weather stations between mid-2007 and mid-2010 were used. The RMSE values ranged between 0.163 and 0.185, and the MBE values ranged between −0.136 and 0.156. To improve the model, the equation used in estimating the clear sky diffuse horizontal irradiance was recalibrated to match better the unique atmospheric conditions in the UAE [21]. The proposed recalibration had led to RMSE values between 0.095 and 0.103, and MBE values in the range −0.01200 to 0.00800 (see Table 1) [21].

Remote sensing techniques have also been used by NASA in its Surface meteorology and Solar Energy (SEE) website, where 22-year average of solar radiation data can be downloaded [30]. We have downloaded the values of the monthly average of the daily values of global horizontal irradiation (GHI), and compared them with those reported in the literature. As shown in Table 2, the 22-year average data is in good agreement with the data measured in Abu Dhabi (Masdar City) for the years 2009–2011, and also with the data reported in the literature since 1971.

4.3. Analytical and semi-analytical correlation techniques

Several analytical and semi-analytical models have been developed to predict solar radiation parameters in the UAE. Al Mahdi et al. have assessed the accuracy of several solar radiation models by using weather data measured in several GCC regions: Abu Dhabi, Bahrain, Doha, Kuwait and Riyadh [31]. The models were of two groups: the first group correlates the monthly average daily values of GHI to sunshine hours, while the second group estimates clear sky radiation and cloud cover effects in order to determine the monthly average daily values of GHI. With regard to the first group of models, in one model, only sunshine duration measurements were used, while in the other models additional parameters were taken into account: geographical parameters such as latitude angle and altitude, and metreological factors like atmospheric temperature, humidity, optical properties of the cloud cover, ground reflectivity and average air mass. When the first group of models was used, data measured in Abu Dhabi City was the least consistent with RMSE and MBE values in the range 0.042–0.127 and (−0.12500)–(−0.03700), respectively [31]. With regard to the second group of models, six different sky models were used, and better results were obtained with RMSE values in the range 0.035–0.087 and MBE values in the range (−0.08500)–(−0.03000). For the RMSE and MBE values obtained for each model see Table 1 [31].

Abdalla et al. have also used the semi-analytical approach to predict the monthly average daily values of GHI in Abu Dhabi City by using the sunshine durations measured during 10 years [32]. Unlike Al Mahdi et al. who have used the same correlation for all the GCC regions, Abdalla et al. have modified the correlation law to match the data measured in Abu Dhabi City. In addition, two other correlation laws were developed and used to predict values of diffuse horizontal irradiation (DHI) values, but because the unavailability of ground measurement data of DHI, the authors were not able to assess the accuracy of the obtained correlation laws.

Khalil and Alnajjar have used ground measurement data recorded in Al-Ain City between 1990 and 1993, and they developed a model to estimate the clearness index, as well as GHI and DNI values [33]. Their model was based on estimating the optical properties of the atmosphere by using the correlations reported in the literature. No RMSE and MBE values were reported, but the authors claimed that good estimations can be obtained under clear sky conditions.

El-Nashar has used global and diffuse solar irradiation values recorded in Abu Dhabi City during the year 1987 to develop a model for estimating the instantaneous values of the clear index, the diffuse fraction (ratio of DHI to GHI), the atmospheric transmittance and extinction coefficient [34]. It was revealed that correlations between these parameters depend on the air mass and month of the year. Therefore, regression formulas were developed to correlate the aforementioned parameters against the air mass and the month of the year. Although no RMSE and MBE values were reported, the author claimed a good agreement between the data measured and calculated by using the regression formulas obtained.

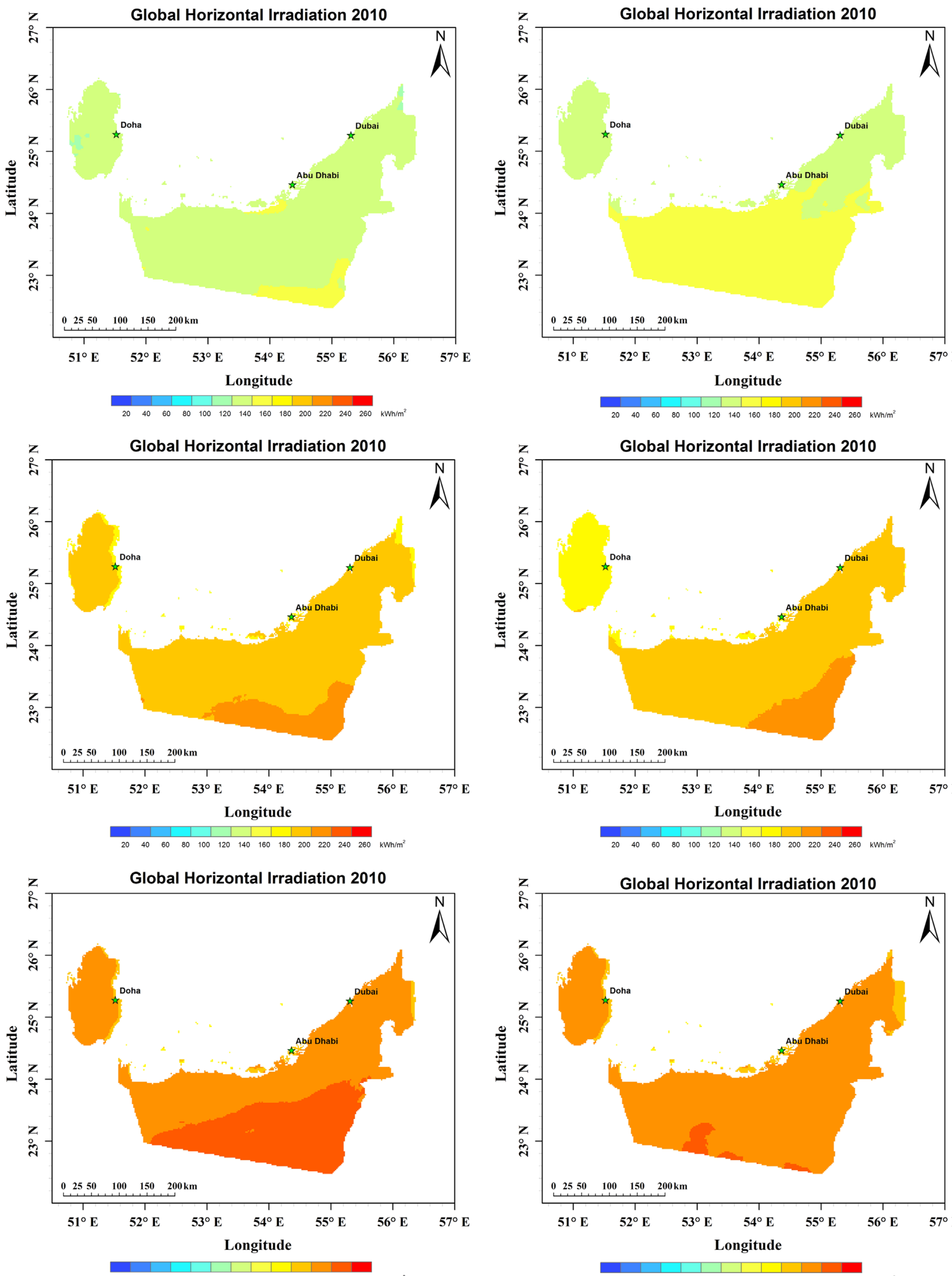

Fig. 23. Monthly GHI maps obtained by processing satellite and ground measurement data (January through June 2010) [29].

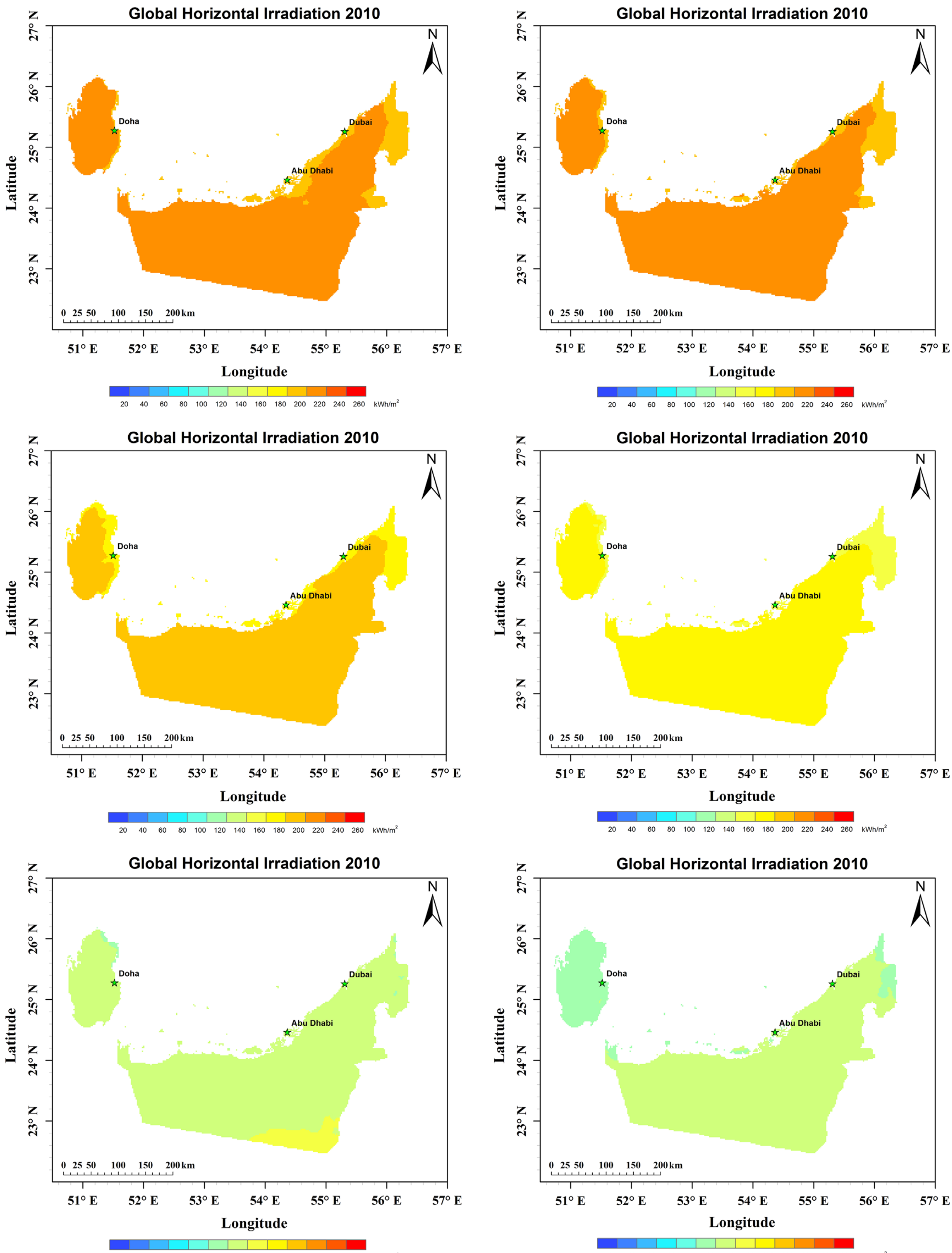

Fig. 24. Monthly GHI maps obtained by processing satellite and ground measurement data (July through December 2010) [29].

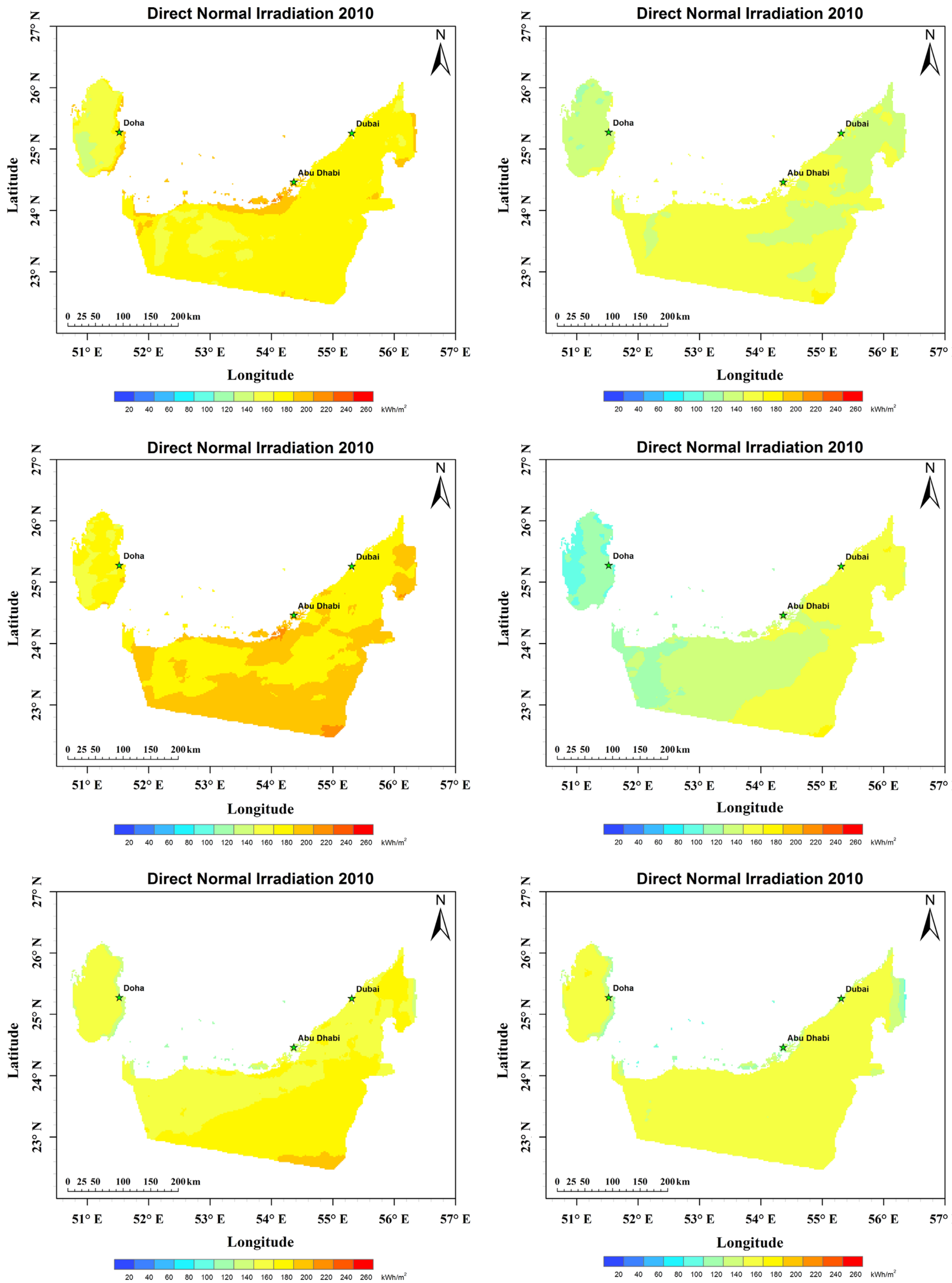

Fig. 25. Monthly DNI maps obtained by processing satellite and ground measurement data (January through June 2010) [29].

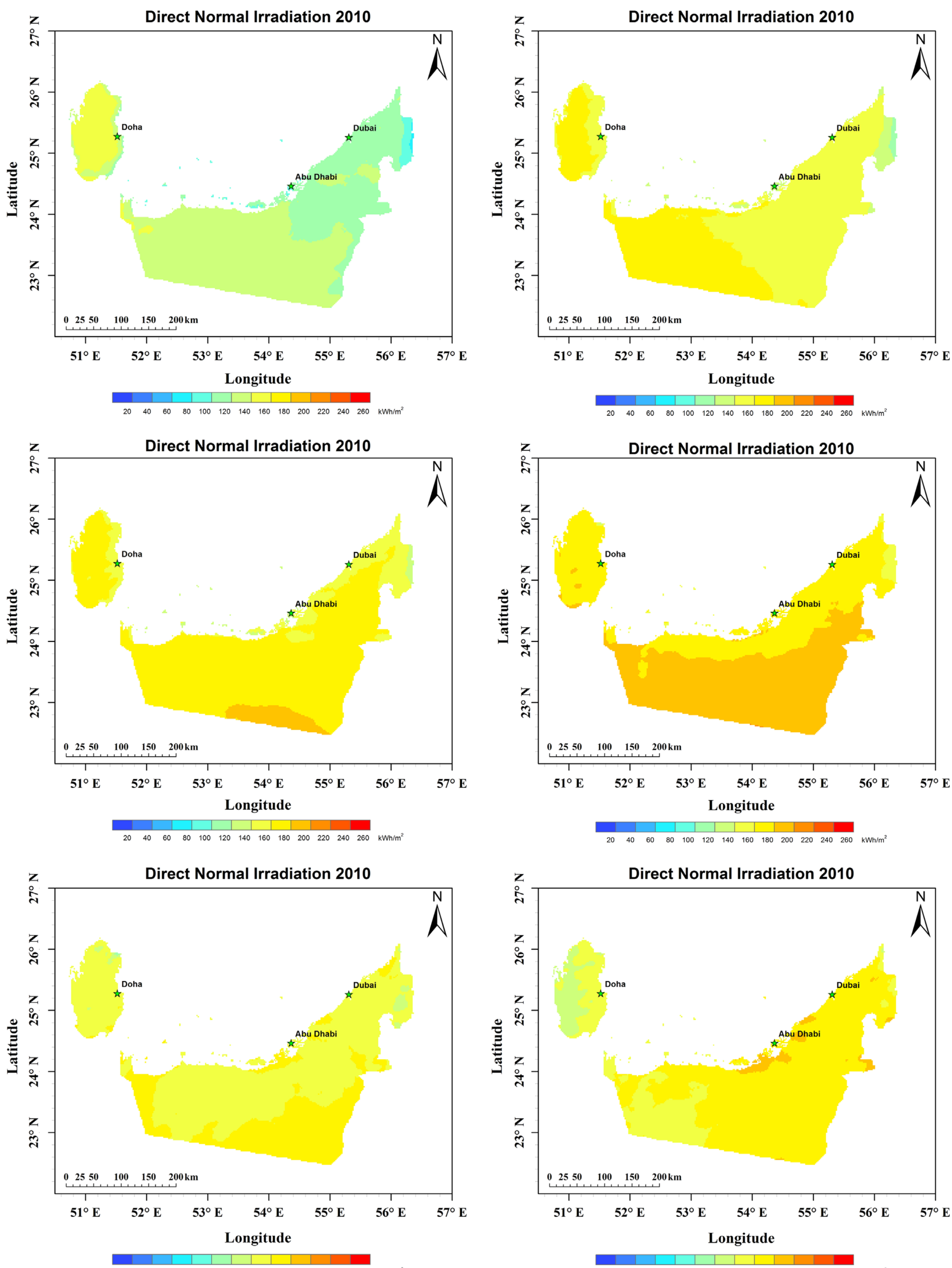

Fig. 26. Monthly DNI maps obtained by processing satellite and ground measurement data (July through December 2010) [29].

Table 2
Ground measurements of GHI in Abu Dhabi between 1971 and 2011.

Months	Global radiation ($MJ/m^2/day$)									
	Abdella et al. (average 1971–1980) [32]	El-Nashar (1985) [34]	WRDC (1992) [40]	WRDC (1993) [40]	ALESCO 10-year overage [35]	NASA SEE 22-year average [30]	Islam et al. (2007) [37]	2009	2010	2011
January	12.17	15.47	12.65	14.99	15.48	14.72	14.08	14.08	15.62	13.01
February	15.52	20.98	17.82	17.24	18	17.28	17.42	17.12	17.85	17.76
March	17.78	22.04	18.99	20.75	20.54	18.83	20.63	19.85	22.12	21.27
April	21.46	25.97	24.05	21.27	24.12	22.75	22.79	23.93	23.70	21.84
May	23.58	26.56	27.19	25.52	27.36	25.85	25.06	26.54	25.14	25.88
June	22.97	28.31	28.85	26.69	27.36	26.03	24.62	25.53	25.64	25.69
July	21.74	24.32	26.08	24.82	25.20	23.22	24.52	24.00	23.78	23.98
August	20.41	24.39	24.64	23.77	24.12	22.75	23.51	23.24	24.18	23.33
September	19.44	24.02	23.99	22.01	23.40	21.78	22.32	22.79	22.53	22.32
October	17.17	20.79	20.27	18.94	20.52	19.40	19.40	19.31	19.33	19.03
November	14.62	17.28	17.19	15.83	17.28	16.31	15.26	16.05	15.68	15.71
December	12.38	14.54	14.31	14.04	14.40	13.61	11.30	12.73	14.93	14.63
Total	6676.05	8045.83	7806.93	7484.41	7884	7371.54	7330.96	7460.61	7624.67	7439.42

Table 3
Ground measurements of the GHI in Abu Dhabi and other regions around the globe (Unit: $MJ/m^2/day$).

	January	February	March	April	May	June	July	August	September	October	November	December	Yearly average
Abu Dhabi, UAE (2011)	13.01	17.76	21.27	21.84	25.88	25.69	23.98	23.33	22.32	19.03	15.71	14.63	20.38
Ghardaia, Algeria (2007) [46]	14.05	16.26	22.51	24.39	28.24	29.34	29.22	24.95	21.31	17.72	15.63	12.54	21.35
Durban, South Africa (2007) [47]	23	22.10	17.17	13.90	13.10	10.12	11.41	13.36	14.76	14.65	17.46	21.35	16.02
Andalucia, Spain (2003–2006) [48]	9.64	12.00	15.54	20.31	23.6	26.48	26.84	24.00	19.1	13.11	9.77	8.15	17.38
Las Vegas, Nevada (2011) [45]	11.73	15.84	19.37	25.56	28.85	31.68	26.62	26.56	20.46	17.03	12.34	10.16	20.53
South Park, Colorado (2011) [45]	10.71	14.75	19.70	23.58	24.25	27.38	22.69	21.54	18.36	15.67	12.25	9.58	18.38
Phoenix, Arizona (2011) [45]	13.47	16.34	21.60	26.20	29.77	31.02	28.01	24.91	21.84	17.86	13.18	10.87	21.28
Lanai, Hawaii (2011) [45]	14.57	15.80	17.77	19.21	17.59	17.39	17.63	16.90	17.40	15.90	13.67	14.15	16.50
Los Angeles, California (2011) [45]	11.98	15.97	18.36	24.27	27.38	24.05	26.19	24.07	18.08	15.43	11.55	11.12	19.06
Elizabeth City, North Carolina (2011) [45]	7.91	12.17	14.01	19.86	22.40	23.58	23.53	20.42	15.46	13.62	9.74	8.16	15.92

4.4. Ground measurements

Several studies report on ground measurement of weather parameters in different regions in the UAE. In 1998, the Arab League Educational, Cultural and Scientific Organization (ALESCO) published the first solar radiation atlas for the Arab world [35,36], which was based on ground measurement of sunshine duration, global solar radiation and diffuse solar radiation in 207 cities. It was shown that, based on the aforementioned solar radiation parameters recorded in Abu Dhabi City, Al-Ain and Sharjah, that UAE has among the highest yearly solar energy input in the Middle-East and North-Africa (MENA). However, Al Mahdi et al. have compared global solar radiation data recorded in several GCC regions: Abu Dhabi, Bahrain, Doha, Kuwait and Riyadh; and it was found that Abu Dhabi City has the least annual amount of global solar radiation, but also the lowest annual average clearness index, and the second highest annual duration of sunshine after Doha [31].

Islam et al. have reported global solar radiation values measured in Abu Dhabi City during the full year of 2007 (see Table 2) [37]. The highest daily maximum value of GHI was 1041 W/m^2, which was recorded in February and the highest daily average value was 369 W/m^2 and it was recorded in May. The daily average energy input was estimated at 18.48 $MJ/m^2/day$. The monthly average clearness index was estimated between 0.54 and 0.66. In a separate study, Islam et al. have reported the direct normal irradiation values (DNI) recorded during the full year of 2007 [38], and the highest daily average and the highest monthly average values were reportedly 730 W/m^2 and 493.5 W/m^2, respectively. Abdalla et al. have also reported the monthly averages of global solar radiation measurements in Abu Dhabi City for the period 1971–1980 (see Table 2) [32]. The monthly average clearness index was estimated between 0.50 and 0.60. El-Nashar has also reported the monthly averages of the global solar radiation values recorded in Abu Dhabi City during the year 1985 (see Table 2) [39]. These parameters for the years 1992 and 1993 can also be downloaded at the World Radiation Data Centre (WRDC) website which served as a depository for solar energy data collected in over 1000 weather stations around the globe [40,41].

For more solar radiation parameters about the UAE, which are recorded within the last few years, they can be accessed by using the software package Meteonorm, which offers data recorded in several weather stations across the UAE including Abu Dhabi airport [41,42]. Table 2 shows the monthly average of global horizontal irradiation in Abu Dhabi as reported in the aforementioned sources in addition to those measured in 2009, 2010 and 2011 in Abu Dhabi City.

With regard to the solar radiation parameters measured in other regions other than Abu Dhabi City, Khalil et al. have reported ground measurement values recorded between 1990 and 1993 in Al-Ain City [33]. The monthly average clearness index was estimated between 0.57 and 0.69. Unlike the observations in Abu Dhabi City, the highest and lowest monthly averages of GHI were observed in December and July.

El Chaar et al. have reported the monthly averages of GHI values recorded between 2007 and 2009 in five different stations in the Emirate of Abu Dhabi, and calculated the corresponding clearness index. The locations are: Al Aradh, Madinat Zayed, Sir Bani Yas, Al Raha and Al Mirfa and it was reported that all have similar monthly averaged GHI values, except Al-Aradh which had higher values especially during the period January through May [43].

Table 4
Hourly distribution of GHI in Abu Dhabi (Unit: hours).

Irradiance (*W/m²*)	January	February	March	April	May	June	July	August	September	October	November	December	Total number of hours
0	436	375	392	364	354	336	352	366	372	407	412	435	4600
50	34	23	26	28	26	27	29	27	23	24	24	24	314
100	22	16	19	21	18	18	21	19	18	18	18	19	227
150	23	16	16	21	17	18	20	16	15	16	16	17	209
200	22	16	17	18	16	15	19	17	14	15	16	16	200
250	22	14	16	17	17	16	15	15	15	15	17	18	197
300	20	14	14	17	13	14	16	16	13	16	17	17	185
350	20	17	16	16	14	14	16	14	14	14	19	18	192
400	19	15	15	17	16	14	14	15	14	16	21	20	195
450	19	13	15	15	14	16	16	14	14	16	19	23	193
500	18	15	16	16	15	14	18	18	16	15	20	21	201
550	19	17	17	16	16	17	17	16	14	18	19	28	211
600	22	18	18	16	16	16	16	18	18	20	23	34	233
650	28	20	19	15	17	18	18	20	18	24	30	45	270
700	16	22	22	14	17	18	23	20	20	28	37	12	247
750	5	31	21	15	19	21	23	26	24	44	13	0	240
800	0	25	22	17	23	24	29	34	31	35	1	0	240
850	0	7	26	20	27	32	41	50	44	3	0	0	249
900	0	0	30	27	39	56	35	22	23	0	0	0	231
950	0	0	11	20	47	18	8	4	2	0	0	0	109
1000	0	0	1	11	4	0	0	0	0	0	0	0	16
1050	0	0	0	2	0	0	0	0	0	0	0	0	2
1100	0	0	0	0	0	0	0	0	0	0	0	0	1
> 1125	0	0	0	0	0	0	0	0	0	0	0	0	0
													8760

Table 5
Hourly distribution of DNI in Abu Dhabi (Unit: hours).

Irradiance (W/m²)	January	February	March	April	May	June	July	August	September	October	November	December	Total number of hours
0	501	403	433	440	377	362	401	397	382	417	426	438	4976
50	20	18	19	31	17	18	29	20	13	12	14	10	220
100	14	15	17	18	15	16	20	17	10	9	10	7	167
150	12	13	16	15	15	15	21	16	10	10	10	8	161
200	10	13	12	12	15	17	20	16	10	10	11	8	152
250	11	11	12	12	18	17	21	20	11	11	11	11	166
300	10	11	11	15	19	21	32	21	13	13	12	11	188
350	9	13	16	14	22	25	27	31	15	14	10	13	207
400	11	19	13	13	19	31	33	36	18	14	14	12	231
450	16	19	12	19	28	38	32	50	19	16	12	14	273
500	16	20	17	19	29	47	41	37	22	22	14	19	303
550	15	22	21	19	30	46	40	45	26	29	17	19	329
600	17	19	22	26	47	43	20	20	37	37	21	22	331
650	20	21	26	25	40	18	6	10	49	46	24	28	311
700	20	16	26	23	35	3	3	8	39	45	25	30	273
750	21	14	26	10	17	4	0	1	35	25	29	36	217
800	11	11	19	3	3	0	0	0	11	11	30	30	129
850	7	12	24	8	0	0	0	0	0	4	25	16	96
900	2	3	4	0	0	0	0	0	0	1	6	11	28
950	2	0	0	0	0	0	0	0	0	0	1	1	3
1000	0	0	0	0	0	0	0	0	0	0	0	0	0
1050	0	0	0	0	0	0	0	0	0	0	0	0	0
1100	0	0	0	0	0	0	0	0	0	0	0	0	0
> 1125	0	0	0	0	0	0	0	0	0	0	0	0	0
													8760

For obtaining solar radiation parameters for other regions, the software package Meteonorm can be used for data recorded in Sharjah airport, Dubai airport, Fujairah airport, Ras Al Khaimah airport, in addition to Abu Dhabi airport [42]. For Ras Al Khaimah in particular, the GHI and DNI values are displayed in real time in the CSEM-UAE company website [44].

In this review, we have used the NREL's US solar radiation database to obtain the GHI values measured in different regions across the US (Arizona, California, Colorado, Hawaii, Nevada, North Carolina) [45], and also obtained the GHI values measured in other regions in the world (Algeria, South Africa and Spain) [46–48], and compared them with those measured in Abu Dhabi in 2011. We select these regions because they host large solar energy markets (Spain and South Africa), and they are known for their excellent solar exposure (Algeria). We have noticed that Abu Dhabi city has a high monthly average of daily GHI values compared with these regions (see Table 3).

We estimate the maximum cumulative time of sunshine in Abu Dhabi at 8760 h, but depending on the application, this quantity may need to be re-evaluated by using the hourly distribution of the GHI and DNI presented in Tables 4 and 5, respectively. Except very few days during the year, the daily sunshine duration ranges

between 10 and 15 h. This means that existing energy storage technologies are technically capable of achieving 24/7 operation.

For the maximum values of GHI and DNI measured in Abu Dhabi city in 2011, they are plotted in Fig. 27. For some months, the value of the DNI is higher than the GHI because that is what the measurement devices indicate under some conditions of zenith angle, therefore, they remain valid. For the monthly average values of GHI and DNI, they are plotted in Fig. 28. From the GHI and DNI plots, we do not notice a significant seasonal variation, which is an advantage for full year operation. Another observation is that the DNI values are high enough for concentrating light, which enables the use of solar concentrating technologies such as concentrated PV, concentrated solar thermal, etc.

4.5. Atmospheric conditions

4.5.1. Attenuation and scattering of sunlight

The UAE environment is characterized by high concentrations of airborne dust particles and high humidity, which tend to diffuse and attenuate the intensity of solar irradiance. Eissa et al. have reported that during heavy dusty days, ground measurement devices provide underestimated values of DNI, DHI and GHI because of the accumulation of dust on the sensors [22]. In this case, the use of satellite data is more reliable to achieve more accurate estimations. During a heavy dusty day, DNI, DHI and GHI values obtained by processing satellite data showed significant overestimations with respect to values obtained from ground measurement stations [21,22]. For instance, MBE values of the DNI estimations in two different locations were 1.44 and 5.40. In a moderate dusty day, the same study reported MBE values of the DNI estimations in the same two locations to be (− 0.0079) and 0.0125; and in a clear day, the values were − 0.007% in both locations. These MBE values and RMSE values shown in Table 6 show that the reliability of satellite data becomes higher with respect to ground measurements during heavy dusty days because of the high RMSE and MBE values observed [22]. Values reported in Table 6 also indicate that the reliability of the two tools depends on the location, and the parameter measured: DNI, DHI or GHI.

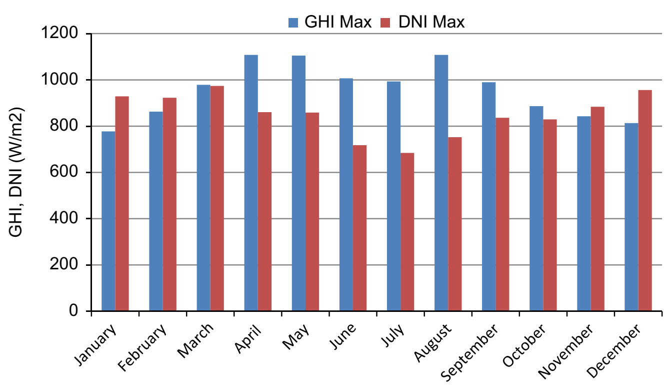

Fig. 27. Maximum values of the global horizontal irradiance (GHI) and direct normal irradiance (DNI).

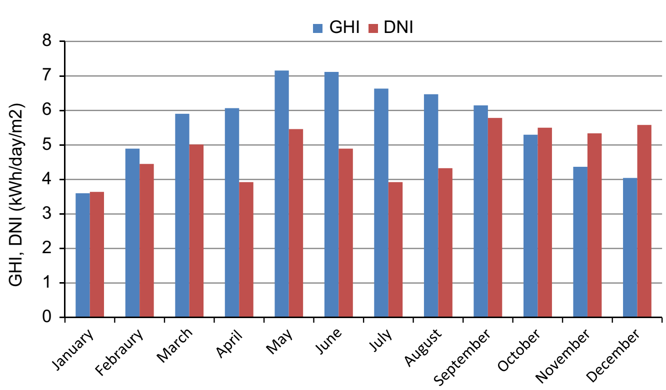

Fig. 28. Monthly average GHI and DNI values.

Parajuli et al. have reported that this effect, which can be quantified as the atmospheric optical depth (AOD), is related to topography, wind speed, soil moisture, surface roughness, and soil properties [49,50]. This means that the concentration of dust (i.e. atmospheric optical depth) in the atmosphere is both location dependent (topography, soil moisture, surface roughness, and soil properties) and time dependent (wind speed, soil moisture) [49,50]. Parajuli et al. have studied the effects of soil moisture and wind speed on the atmospheric optical depth (AOD) in two areas in the Abu Dhabi desert (Mezaira and Hamim), and it was found that the months of May through August witness the highest magnitudes of AOD in both areas. However, the magnitude of AOD was different in these two areas for the reasons discussed above [49,50]. Also, for the same area, and same month of the year, it was found that AOD may vary significantly from one year to another [49,50]. These findings highlight the variability of dust concentration in the atmosphere with both day of the year, from year to year, and the location.

4.5.2. Sunshape profile

The forward scattering of sun rays by atmospheric particles causes the formation of a region around the solar disk called the circumsolar region or the sun aureole. Because DNI measurement devices have a larger acceptance angle than concentrating receivers (CPV, CPC and CSP receivers), they capture a large portion of incoming radiation not only from the solar disk but also from the circumsolar region. Therefore, the actual DNI that is incident on the receiver of an optical concentrator is rather overestimated. Such an overestimation in DNI may lead to some considerable effects on the performance and economics of a concentrating solar installation [51,52]. In order to detect this effect, the sunshape of the solar disk is drawn in Abu Dhabi (Masdar City): the angular brightness distribution of the solar disk and the region around it [53,54].

Technically, two parameters are used to quantify this effect: (1) the circumsolar ratio (CSR) which is the radiant flux contained

Table 6
Accuracy of estimating solar radiation parameters from satellite data with respect to ground measurement data in two locations in the UAE [22].

	DNI		DHI		GHI	
	RMSE (location 1, location 2)	MBE (location 1, location 2)	RMSE (location 1, location 2)	MBE (location 1, location 2)	RMSE (location 1, location 2)	MBE (location 1, location 2)
Heavy dusty day	1.51, 5.58	1.44, 5.40	0.0714, 0.237	0.0229, 0.225	0.172, 0.365	0.159, 0.359
Moderate dusty day	0.12, 0.0615	− 0.0079, 0.0125	0.0997, 0.144	0.016, 0.12	0.0462, 0.0535	− 0.0116, 0.0356
Clear day	0.093, 0.0909	− 0.0714, -0.0743	0.204, 0.27	0.183, 0.252	0.0339, 0.0356	− 0.0067, 0.00575

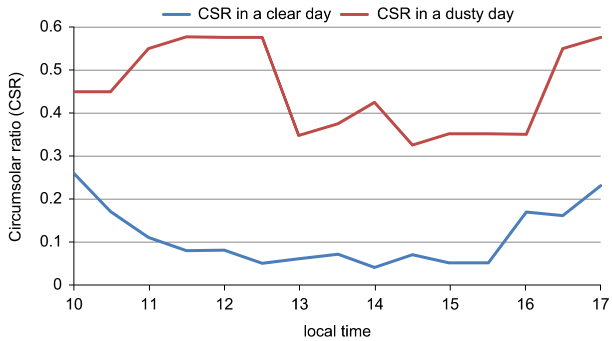

Fig. 29. Estimated values of the circumsolar ratio during a clear and a dusty day [54].

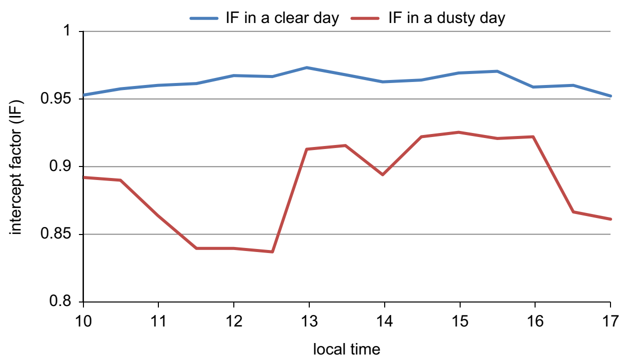

Fig. 30. Estimated values of the intercept factor during a clear and a dusty day [54].

within the circumsolar region of the solar disk divided by the incident radiation coming from both the solar disk and the surrounding region, and (2) the intercept factor which is the fraction of the radiation incident on the absorbing surface (i.e. the receiver) divided by the total radiation which can be possibly received at the receiver [53,54].

In order to study this effect in the dusty environment of the United Arab Emirates, Kalapatapu et al. have developed a device (sunshape rotating radioameter $(SR)^2$) and simulation models to estimate the circumsolar radiation profile and intercept factor. In order to see the effect of these parameters on the performance of concentrating solar systems, values of the CSR and IF during a dusty and a clear day were estimated by Kalapatapui et al. and they are shown in Figs. 29 and 30. From both figures, we see that the CSR affects the intercept factor, and therefore, the amount of energy received at the receiver. For instance, in Fig. 24, we see that the intercept factor drops by 4–12% absolute, which means around 4–12% less radiation is received in a dusty day compared with a clear day [53,54].

5. Operating conditions

5.1. Dust accumulation

As mentioned above, the UAE is known for high levels of atmospheric dust concentrations [21,22,54,55], which causes high dust accumulation on solar collectors [56]. This would lead to: a drop in the energy yield, difficulty in predicting the power output, and additional cost for cleaning. As for the solution to this issue, two methods were investigated: (1) determining an optimal frequency for wet cleaning (i.e. by using water) and (2) adding a self-cleaning coating to the PV modules.

It was mentioned that the effect of dust accumulation on the energy output of the solar panel depends on the following factors: nature and size of dust particles, orientation of the panel with respect to the dominant wind direction, wind speed, humidity, distribution of dust on the surface, the tilt of the panel, geographical position which affects dust concentration levels, temperature, the panel surface properties (e.g. roughness, etc.), amount of sand that is already on the surface (i.e. accumulation history) and whether the panel is stationary or uses tracking [56].

The experimental setup consisted of two similar crystalline silicon modules ground mounted at a fixed tilt. One was kept clean and one was kept unclean. The experiment was run during 10 months in Masdar City, where humidity is high (location close to the sea) and the modules were mounted in a sandy ground [56]. So it should be noticed that the results reported by Zaid et al. are representative of extreme operation conditions, which do not represent other locations in the UAE. Depending on the season, leaving a module unclean for one month resulted in up to 20% drop in energy produced daily. Leaving the module unclean for 2 consecutive months resulted in up to 30% drop in energy produced daily. In some days towards the end of the 2 months period, drop in energy has reached 40%. However, drop in efficiency was not increasing continuously as the module was kept unclean. This is because of events of resuspension: spontaneous removal of dust from the modules by wind, gravity, etc. Another observation from Zaid et al.'s experiment is that during the 2 months testing period, dust kept accumulating without reaching a plateau. It was also found that high wind speeds favor resuspension (i.e. cleaning), and that it seems that there is a minimum wind speed required for this to happen, while low wind speeds favor deposition. It was also mentioned that the direction of wind may favor either deposition or resuspension of dust. Because of the experimental setup set initially, Zaid's et al. could not provide quantitative analysis on the relationship between wind speed, wind direction, dust concentration in the atmosphere, and the amount of dust that remains on the PV module without cleaning it over a period of time [56].

With regard to the second solution, it consists in applying a commercial coating with self-cleaning properties on the PV module [56]. Two crystalline PV modules were ground mounted side by side, with one coated and one left uncoated. It was shown that the coating did not affect the transmission of light, and both modules had the same power output when they were both clean. An optical characterization of a piece of glass coated with the self-cleaning coating, and an uncoated piece of glass showed that the coating did not affect the optical properties of glass noticeably.

When both PV modules were left unclean for a period of 23 days, there was no difference in their output, which means that the coating applied did not show the expected self-cleaning properties. Zaid et al. claimed that this could be due to the fact that some materials lose their self-cleaning properties when exposed to solar radiation (ultraviolet wavelengths). Lack of information on the composition, morphology and manufacturing of the coatings used has prevented further analysis. Therefore, it was suggested that different types of self-cleaning coatings with known characteristics should be tested to see whether this solution works in the local environment or not [56].

In another study, El-Nashar has investigated this effect of dust accumulation on evacuated cube collectors for powering water desalination installations in Abu Dhabi [57]. The collector has an area of 1864 m^2 (1064 units of 1.75 m^2) and the seawater desalination unit has a capacity of 120 m^3/day and it uses the multi-effect (MED) technology. The location of the installation is not far from where Zaid et al. have conducted their experiment [57]. The aim of the study was to evaluate the effect of dust accumulation on the performance of the desalination unit, and to investigate if high

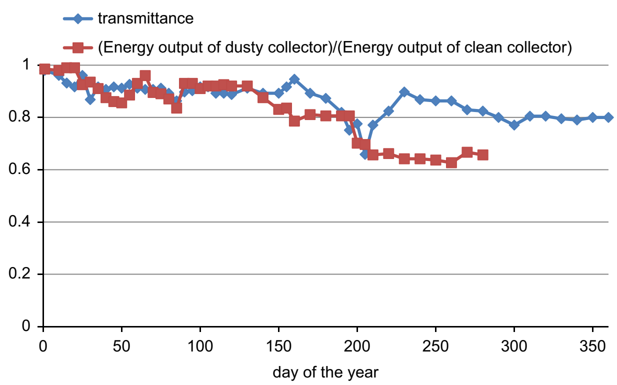

Fig. 31. Transmission and energy yield of dusty evacuated tube solar collectors [57].

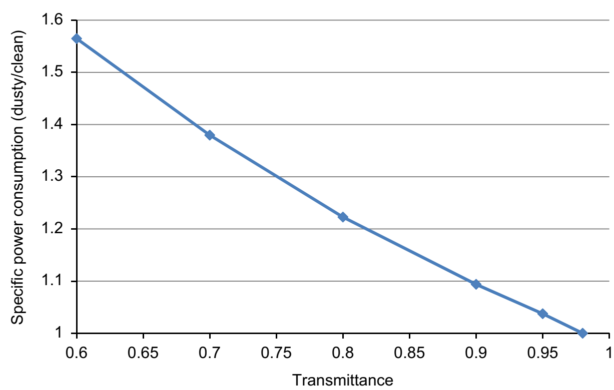

Fig. 32. The relationship between transmittance of thermal solar collectors and specific energy consumption of an MED desalination unit [57].

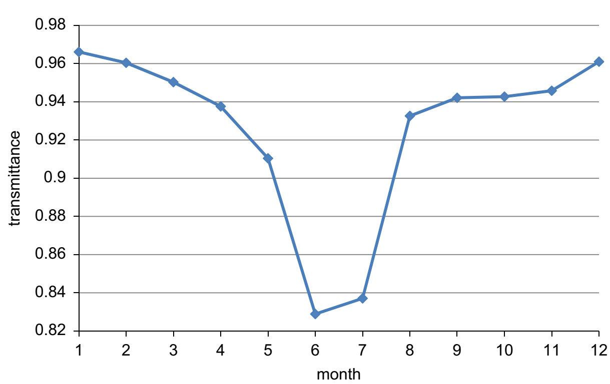

Fig. 33. Transmittance of dusty evacuated tube solar collectors at the end of every month [58].

pressure water jet cleaning is a viable cleaning method. Two similar blocks of collectors, with one maintained clean at all times, and the other one kept unclean, were monitored for a full year. El-Nashar aimed to quantify the effect of dust accumulation by measuring transmission of the collectors, and hence, the reduction in their energy output (Fig. 31). After 10 months of operation, transmission of the dusty module dropped from 98% to 80%, and this has caused the energy output to decrease by up to 40% (Fig. 31) [57]. The same study has found that dust accumulation depends strongly on the season, and therefore, frequency of jet cleaning should be adjusted accordingly [57].

El-Nashar has also studied the effect of dust accumulation on the operation of the desalination unit [57]. It was found that the specific energy for generating a unit of distilled water increases when dust accumulates on the collectors. This is because of two reasons. First, dust reduces transmission, and therefore, the energy output from the collectors which may not be enough for running the desalination process, and consequently, causing an automatic shutdown. In order to bring the desalination back to operation, an additional amount of energy is required prior to starting the production of water. Second, as dust accumulates, less thermal energy is produced, and therefore, less water is produced for the same solar radiation incident on the collectors. In Fig. 32, the relationship between specific energy consumption by the desalination unit and transmission of the solar collectors is presented. The same study has also shown that a constant transmission of 80% during the month would reduce distilled water production by 20–40%, and a transmission of 90% would reduce it by 10–20% depending on the season [57].

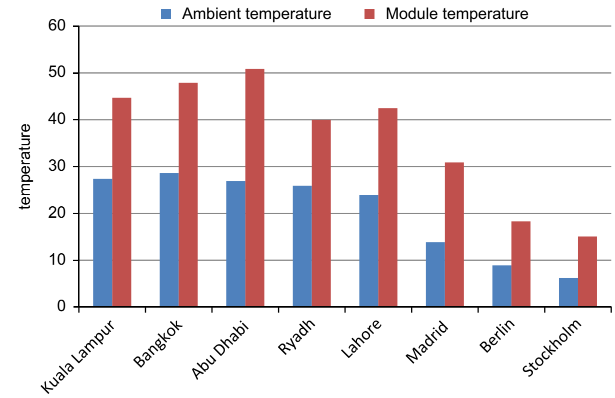

Fig. 34. Yearly average ambient and module temperatures for different locations [59,60].

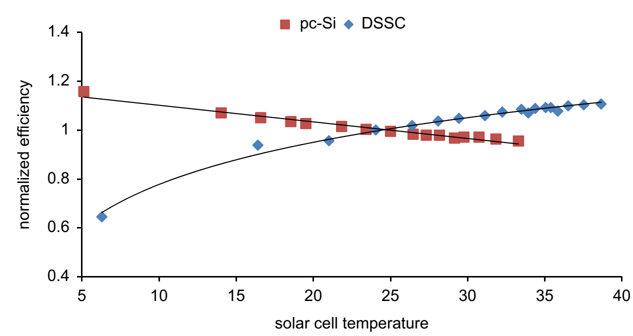

Fig. 35. Effect of temperature on pc-Si and DSSC solar cells [59,60].

The same author published another study in 2009 with a similar scope [58]. In this work, one set of collectors was maintained clean at all times, while the other set of collectors was clean in the beginning of every month for a full year. Transmission measure at the end of every month is presented in Fig. 33, and it shows the seasonality nature of dust accumulation. Interestingly, this conclusion bolsters the results by Parajuli et al. which indicated that dust concentration is highest in the period of May through August of every year [49,50]. In this work, El-Nashar has studied various cleaning frequencies by using a mathematical model and assuming that water used for cleaning is brought from the water produced, and he reported that a weekly cleaning frequency is the optimal scenario for an optimal usage of cleaning water and achieving a high performance [58].

5.2. Temperature

Asghar et al. have conducted a modeling study to investigate the performance of several commercial solar cell technologies in

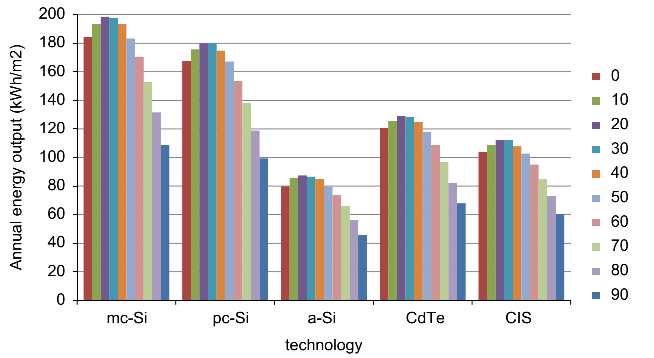

Fig. 36. Annual energy output of different module technologies at different tilt angles [59,60].

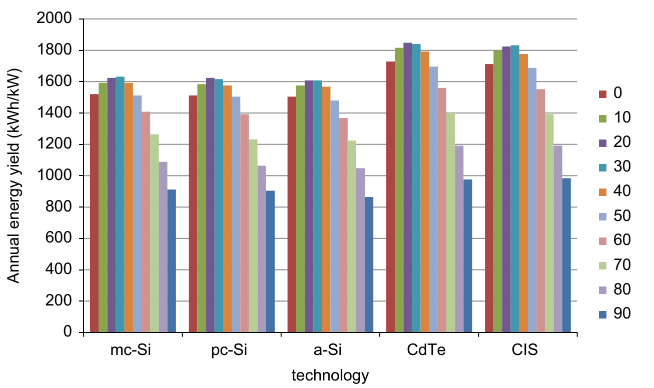

Fig. 37. Annual energy yield of different module technologies at different tilt angles [59,60].

several regions around the globe with different operating conditions: Kuala Lampur, Bangkok, Abu Dhabi, Riyadh, Lahore, Madrid, Berlin and Stockholm [59]. Yearly average temperatures estimated for all sites studied are presented in Fig. 34. It is shown that modules in Abu Dhabi are expected to have the highest operating temperatures [59]. At a tilt of 0°, and under high radiation (1000 W/m^2), module technologies were classified based on their sensitivity to temperature in the following order: CIS, mc-Si, a-Si, pc-Si and CdTe being the technology with the highest temperature coefficient. However, under low moderate radiation (200 W/m^2), module technologies were classified in a different order: mc-Si, CIS, CdTe, then pc-Si and a-Si both having the same highest temperature coefficient. Hence, one could conclude that mc-Si and CIS are the most appropriate technologies for the high temperature operating conditions in Abu Dhabi.

Asghar et al. have tested a dye-sensitized solar cell and a pc-Si cell side-by-side for 2 months in the city of Abu Dhabi, and they reported that the efficiency of the DSSC cell increased when temperature increased, while the efficiency of the pc-Si decreased (Fig. 35) [60].

5.3. *Orientation of solar panels*

In building-integrated PV installations, installers of PV modules are sometimes constrained to place modules on the roof or façade which do not have the optimal orientation. As the tilt angle deviates from the optimal angle, the energy output decreases. Asghar et al. have estimated the effect of the tilt angle on the energy output by unit area (kWh/m^2) and energy yield (kWh/kW) for several module technologies when operated in Abu Dhabi city (Figs. 36 and 37) [59,60]. One can conclude from those results that the optimal angle should be in the range 20–24° for the Abu Dhabi city. Another conclusion is that the energy yield at 0° is 93% of that at the optimal angle, while the yield at 90° is 55% of that at the optimal angle. Interestingly, even when the tilt is 90°, the yield is still higher than that obtained from similar modules installed at the optimum tilt in regions with lower solar radiation such as Berlin and Stockholm [59,60]. In addition to this, the effect of the tilt angle depends on the module technology.

Jafarkazemi and Saadabadi have also attempted to determine the optimal tilt angle for any solar panel, regardless of its technology, in Abu Dhabi city [61]. For this purpose, a model was built to find the optimal angle for the full year, and also the monthly, the seasonal and the bi-annual optimal tilt angles. It was found that the optimal tilt angle is not equal to the latitude of the location but 22°. This finding does not contradict the results reported by Asghar et al. [59–61].

6. Technological solutions

Asghar et al. conducted a comparative modeling and experimental study to investigate the performance of several commercial solar cell technologies (mono-crystalline silicon (mc-Si, 12.22% efficiency), poly-crystalline silicon (pc-Si, 11.10% efficiency), amorphous silicon (a-Si, 5.40% efficiency), cadmium telluride (CdTe, 6.92% efficiency) and copper indium sulfide (CIS, 6.41% efficiency)) [59,60], in addition to 16 different types of dye-sensitized solar cells in the city of Abu Dhabi. All mainstream technology modules (mc-Si, pc-Si, a-Si, CdTe and CIS) were assumed to have a power rating of 50 W, and their performance was compared based on the ratio: energy output to the maximum rated power (kWh/kW). The model takes the radiation and temperature of the site into account, in addition to the orientation and performance characteristics of the PV modules (e.g. efficiency, temperature coefficient, etc.). Here, it is worth mentioning that the model does not take effects of dust accumulation, sunshape, etc. into account which may affect the conclusions below.

As mentioned earlier, it was concluded that mc-Si and CIS are the most appropriate technologies for the high temperature operating conditions in Abu Dhabi.

Asghar et al. have also studied the viability of integrating dye-sensitized solar cells (DSSC) in buildings in Abu Dhabi city. For this purpose, 16 different DSSC cells and modules with area in the range 9–645 cm^2 were placed at a tilt of 24° and tested outdoors for two months (February and March). The cells all had moderate efficiencies in the range 0.34–3.9% at standard conditions. It was observed that the efficiency of the DSSC cell increased when temperature increased, while the efficiency of the pc-Si decreased

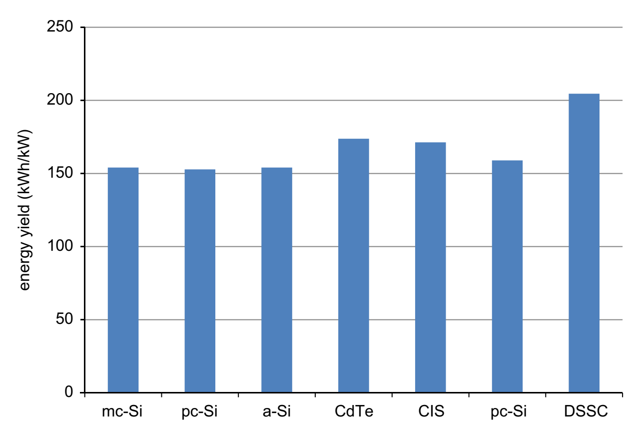

Fig. 38. Energy yield of different module technologies during a 15-day testing period [59,60].

[59,60]. This puts the DSSC technology in an advantage because of the relatively high temperatures in the UAE.

When the effect of irradiance was studied, the conclusion was that, as irradiance decreases, the efficiency of the pc-Si decreases exponentially. However, for the DSSC, as irradiance decreases, the efficiency increases slightly in a linear fashion until irradiance falls below 100 W/m^2 when efficiency increases exponentially. This observation is particularly interesting because it means that during low irradiation periods (after sunrise, before sunset, during cloudy or very dusty periods), the output of the modules does not drop significantly unlike other mainstream PV technologies.

Asghar et al. have also studied the long time stability of the DSSC cells, and it was reported that all degraded at different rates, and none of the cells maintained its performance during the testing period of 2 months. In fact, some were totally not functional before the 2 months time span. For one of those that remained functional, during two consecutive 15-day testing periods in March and April, it showed a 28% higher yield than the pc-Si cell (Fig. 38) [59,60].

DSSC can be regarded as a branch of the organic solar cells family, and therefore, it has similar operation. Sondergaard et al. have tested 10 different types of organic solar cells and modules in eight different locations in Europe to study their outdoors stability during a period of 4 months and a half [62]. The study showed that solar modules installed in coastal regions suffered from more degradation compared with those installed inland because of the high concentration of salt in air. Here we recall that high salt concentration in air favors corrosion of the solar cell electrodes. It was also found that exposure to the sun radiation (photodegradation) is not the major mechanism of degradation in the solar cells tested. Another issue to stability is temperature fluctuations which cause some components of the solar cell to detach. Sondergaard et al. reported that, after the 4 months and a half of outdoors testing, the efficiency of all modules dropped by around 40% in average [62]. This represents an improvement over other research results because of the novel encapsulation method used in the solar cells and modules tested. Therefore, better encapsulation methods are called for to achieve a better outdoors stability.

Gevorgyan et al. have also studied the effect of the atmosphere on the degradation of a generic type of organic solar cells, and it was found that humid environments contribute significantly towards degradation [63]. This observation is particularly useful to us because the UAE's built environment is concentrated towards the sea where humidity is high. Therefore, to achieve a long term stability, the design of the organic solar cells should be protective from water [63].

7. Solar energy projects

In this part of the study,[1] we aim to develop a solar installations map for the UAE (Fig. 39), where all installations with a capacity of around 50 kW and above are presented. Some of these installations has already been covered elsewhere [64]. For this purpose, we collected information on virtually all mid-size and large-size solar installations in the country. We present projects in the following orders: medium size PV and water heating installations (larger than 50 kW and smaller than 5 MW), large solar power plants (5 MW and above), and R&D demonstration projects. Then we cover projects that operate outside the UAE.

7.1. Solar rooftop plan (SRP)

The solar roof plan in Abu Dhabi is a government sponsored financial incentive program designed to make the use of solar photovoltaic on rooftops more affordable to Abu Dhabi building owners. This project is led by Masdar and the Abu Dhabi electric utility ADWEA. SRP is a step further to reach the target of Abu Dhabi for achieving 7% renewable energy capacity in UAE by 2020 (i.e. a capacity of 1500 MW). The program aims at achieving 500 MW PV on rooftops within 20 years [63].

In the context of this program, so far, 11 governmental buildings have been fixed with a cumulative rooftop capacity of 2.3 MW that will generate 4.025 GWh/yr of electricity and save 3220 t of carbon dioxide per year. Those installations are: Sheikh Sultan Bin Zayed Mosque (55 kW), Crown Prince Court (300 kW), Al Mamoura (210 kW), Abu Dhabi Distribution Company (125 kW), Abu Dhabi National Exhibition Centre (100 kW), Armed Officer's Club (100 kW), Al Ameen School (50 kW), Abu Dhabi Aircraft Technology (300 kW), Masdar Institute of Science and Technology (1 MW), and a private villa (15 kW). This pilot project will help develop a performance history for PV installations under the unique environmental conditions in Abu Dhabi city, and design the financial incentive scheme of the program which consists of three elements: a rebate payment at the moment of investment, a tariff paid for each kWh fed to the grid, and this tariff will decrease annually to encourage new system owners to adopt technological developments.

7.2. Solar car park shade structures

Because of the high temperatures, installing shading structures for cars is the norm in outdoor parkings in the UAE. In our survey to make a solar installations map, we noticed that several PV installations are put on the roofs of these shading structures to achieve cumulatively 1.65 MW (see Table 7).

One of these systems has been installed in the interim headquarters of Masdar in Masdar City with a power capacity of 204 kW which translates into 343 MWh/yr, representing a saving of 300 t of CO_2 emissions per year. The project was designed and constructed by Enviromena and it consists of 105 parking slots that protect the cars from the sun heat and provide shading for outdoor walkways. The structures consist of 650 mono-crystalline silicon modules of 315 W.

7.3. Installations in remote islands

Around 7% of the UAE land is islands, and several of those islands are host to oil and gas refineries and other activities that require transporting fuel to them by air or by sea. For a more reliable energy supply, two islands already have PV installations: Al Qarneed Island (0.75 MW), and Marawah Island (0.49 MW), to achieve a cumulative capacity of 1.24 MW (see Table 7).

7.4. Other PV installations

One installation is the Shams Tower, a solar PV installation located on the wings of the Shams Tower in the Yas Marina Formula 1 circuit, a VIP hospitality building rising 60 m from the track, with an area of 2500 m^2, giving a total power capacity of 291 kW and energy production of 450 MWh/yr, representing a saving of 400 t of CO_2 emissions per year. The project timeframe was about 16 weeks with a life span of over 25 years. These PV panels will shade the car park and provide some energy to the Yas Marina circuit (see Table 7). The PV system consists of 1120 polycrystalline silicon modules.

7.5. Water heating installations

There are several water heating installations across the country, and among those are four on iconic buildings: Burj Khalifa in

[1] Information in this section is the authors' own compilation. It is based on interviews, talks from several events, and press releases.

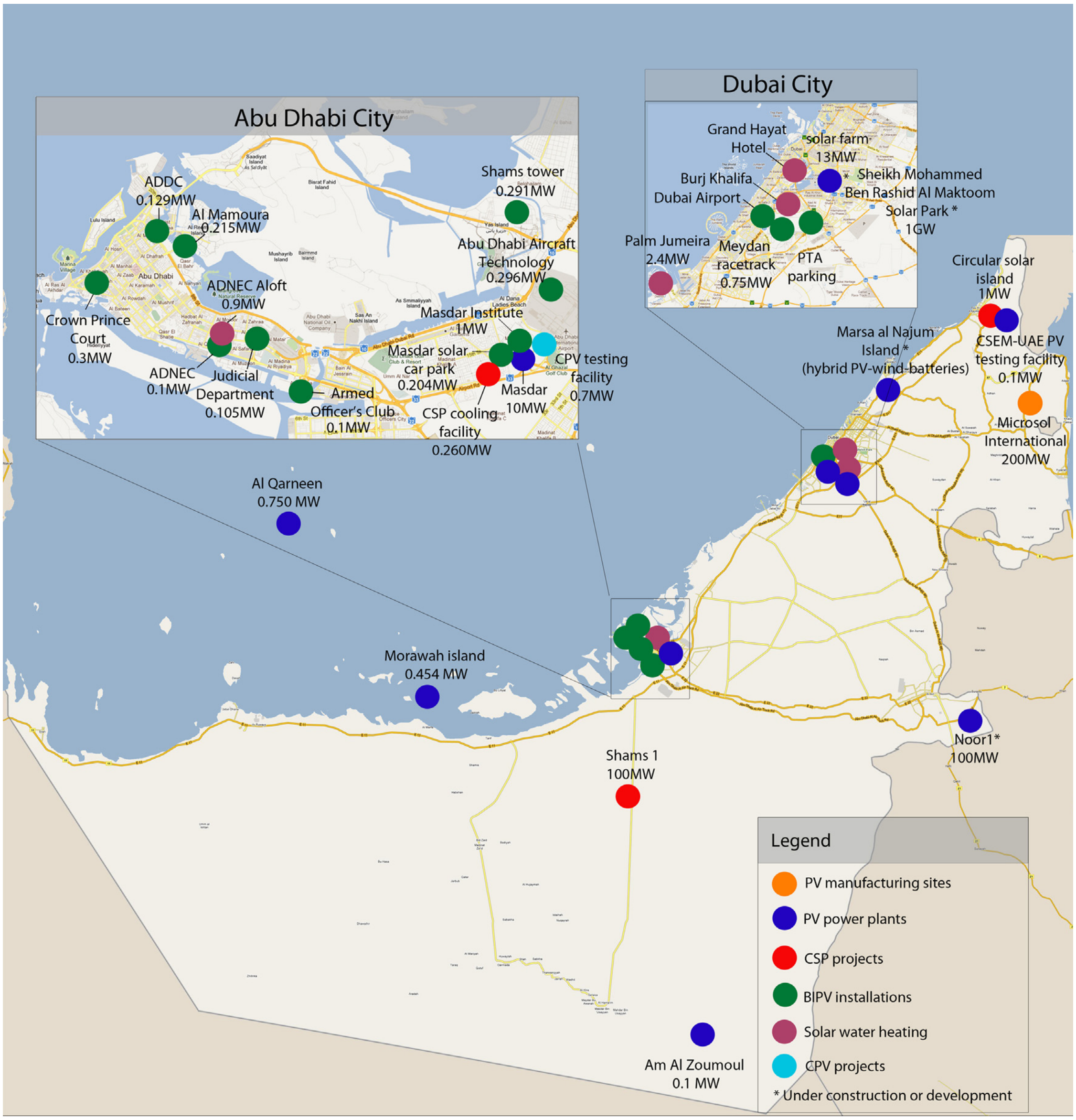

Fig. 39. The solar installations map for the UAE.

Dubai, Palm Jumeirah in Dubai, Aloft Hotel in Abu Dhabi and Masdar Institute in Abu Dhabi. Our observation is that mid-size and large-size water heating installations are usually installed in Hotels: Al Bustan Totana Hotel in Dubai (120 kW), Sea Palace in Abu Dhabi (68 kW), Ajman Palace Hotel in Ajman (157 kW), etc. Cumulatively, we counted a 4 MW of solar water heating capacity country wide.

Regarding the PV and concentrated solar power (CSP) large power plants, they are:

7.6. Masdar 10 MW PV power plant

This power plant was officially inaugurated in June 2009 and was designed and constructed by Enviromena. This plant with an area of 218,000 m^2 with 87,336 PV modules installed on light weight steel racking and 200 km of wiring is producing about 17,500 MWh of electricity per year. This makes it the first, and by far, the largest grid connected solar PV plant in the Middle East and North Africa. There are two types of solar PV module technologies being used in this power plant: crystalline silicon modules (18,288 units) to supply around 5 MW, and CdTe thin-film modules (69,048 units) to supply another 5 MW.

7.7. Shams 1 concentrated solar power plant

It is one of the world's largest concentrated solar power plants (located in Madinat Zayed in the desert of Abu Dhabi) and the first of its kind in the Middle East. Shams 1 started operation in the first quarter of 2013, and it is a joint project between Masdar (60%), Total (20%), and Abengoa Solar (20%). Shams 1 extends over an area of 2.5 km^2 with an approximate capacity of 100 MW. The solar field consists of 768 parabolic trough collectors supplied by Abengoa Solar. This project generates efficient solar thermal electricity from concentrating sunlight by parabolic mirrors to heat a fluid which generates a high-pressure steam to drive a conventional steam turbine. The construction of this project started in the 3rd quarter of 2010. Shams 1 plant will offset about 175,000 t of CO_2 per year, which is equivalent to planting 1.5 million trees or removing 15,000 cars from the roads of Abu Dhabi.

Table 7
Other solar installations in the UAE.

	Location	Capacity (MW)	Operation date
Parking structures			
Dubai Airport PV parking shades	Dubai Airport	–	2011
Sahel Worker Camp off grid PV	Worker camp 120 km southwest of Abu Dhabi	0.0522	2012
PTA parking meters and DEWA street and car parking lighting	Dubai	< 1.35	–
Roof-mount			
Meydan Racetrack	Meydan Racetrack, Dubai	0.75	2010
Abu Dhabi West School	Abu Dhabi	0.075	2012
Abu Dhabi- Municipality Building	Salam Street office, Abu Dhabi	0.1	2011
Al Khatim School	Abu Dhabi	0.047	2011
Al Khazna School	Abu Dhabi	0.054	2011
Al Towaya School	Al Ain	0.065	2011
Dahar B School	Al Ain	0.065	2011
Al Jahly School	Al Ain	0.085	2011
Mezyad B School	Al Ain	0.065	2011
Emrill	Dubai	0.072	2012
Ground-mount			
Al qarneen island	Al qarneen island	0.750	2011
Am Al zoumol	Am Al zoumol	0.100	2011
Morawah island	Morawah island	0.494	2011
Solar thermal			
Masdar Institute 1A water heating system	Masdar City, Abu Dhabi	–	2010
ADNEC Aloft Hotel Solar water heating system	Roof of ADNEC Car Park, Abu Dhabi	0.9	2009
Palm Jumeira Solar water heating	Palm, Jumeira, Dubai	2.4	–

7.8. Noor 1 PV power plant

It is a 100 MW PV solar power plant to be built in Al-Ain region in Abu Dhabi [65]. The project is still at the development phase and not much information has been released on it so far.

7.9. Sheikh Mohammed bin Rashid Al Maktoum solar park

The Supreme Council of Energy in Dubai aims to ensure availability and reliability of energy supply while preserving natural resources through effective steps to address the challenges of climate change and the application and development of renewable energy technologies [66]. For this purpose, the Super Council of Energy developed Dubai Integrated Energy Strategy 2030 to ensure sustainable sources of energy supply as a primary factor that supports economic growth. This strategy will diversify energy sources in the emirate to increase renewable energy sources to 1% by 2020 and 5% by 2030 [66]. It is worth mentioning that Dubai is 120 km north of Abu Dhabi city, and it has a similar climate and solar exposure.

The introduction of renewable resources in Dubai's energy portfolio will take two forms: distributed solar generators installed by clients (in rooftops or ground mounted), and solar power plants.

Sheikh Mohammed Bin Rashid Al Maktoum Solar Park is part of Dubai's energy diversification initiatives to meet its renewable resource contribution targets [66]. The solar park is located in Seih Al-Dahal, the area of 48 km^2 is enough to construct plants (PV and CSP) with a total capacity of 1000 MW by 2030. This solar park will be the largest in the region. The first part of the park has already started, which is a PV plant with a capacity of 13 MW, that uses First Solar's CdTe thin film modules, and the plant is self-funded by members of the supreme council of energy (SCE) [66].

7.10. R&D pilot projects

Because of the potential of solar energy in the UAE and its short history of performance, several companies and research institutions are working on pilot projects to develop an understanding of how different solar technologies perform under the real operating conditions. Some of these pilot installations are based on some exotic technologies that are not in the market yet such as a floating solar installation and a beam-down concentrator, while others use mainstream technologies.

7.10.1. Masdar PV testing facility

The testing site is built in Masdar City and it houses 26 units of 1 kW PV modules mounted on aluminum structures. It began its operation in 2007. The purpose is to test different PV technologies in the hot, humid and sandy conditions and rank them according to their performance. The results determine, therefore, which technologies are best under these conditions. It is also the host of several R&D projects on the effect of dust accumulation on solar panels, the methods of cleaning solar panels, etc. This facility will also help determine the size and technology needed to feed Masdar City in the long term. The testing site was the first grid-connected solar power system in Abu Dhabi.

7.10.2. The solar cooling installation in Masdar city

It is the first double-effect solar thermal cooling system in the Gulf region, and it uses the sun's heat to cool buildings in Masdar City. Moreover, it merges two different solar concentration technologies in a single system: parabolic trough collectors with uniaxial tracking and a total mirror aperture area of 334 m^2 with a power capacity of about 200 kW, and linear Fresnel collectors with uniaxial tracking and a total mirror aperture area of 132 m^2 with a capacity of 60 kW. Basically, the system uses double-effect absorption chillers that use heat to activate a chemical process that provides chilled water for cooling. The parabolic troughs collect sunlight to heat circulating oil. Heat is exchanged via a pressurized water circuit and the Fresnel collectors heat the water. Already operational, the pilot project cools 1700 m^2 of Masdar's offices space resulting in 75% energy recovery and about 70 t of emissions reductions.

Fig. 40. The beam-down solar concentrator in Masdar City, Abu Dhabi.

7.10.3. Beam-down solar concentrator in Masdar city

It is a joint project between Masdar, Tokyo Institute of Technology, Mitsui Engineering & Shipbuilding and Cosmo Oil based in Japan (Fig. 40). It works by reflecting the solar radiation from ground mirrors to another set of mirrors called secondary mirrors at the top of the tower. These mirrors direct the radiation to a concave receiver at the base of the tower that heats a fluid to generate steam. The mirrors on the ground are 33 and all have double-axis tracking. In such concentrators, the receiver is put on the ground which, among several benefits, obviates the need for pumping fluids to the top of the tower like in conventional central receiver solar concentrators. It is interesting to mention that there is no power plant using this concentrating technology yet.

7.10.4. The concentrated PV testing facility (CPV)

It is a joint project between Masdar and ISFOC (Spain) that will test various concentrated PV (CPV) systems under Abu Dhabi environmental conditions. This project is being implemented in Masdar City. The CPV pilot project aims to connect 1 MW of CPV electricity generation to the electrical grid with a minimum power of 100 kW for each system tested. The reliability and the cost reduction of CPV is the main focus of this project. The authors of this review have reviewed the current status of this technology and the market, and it was shown that CPV has the highest cost reduction potential among mainstream solar technologies especially in areas with high DNI such as the UAE.

7.10.5. The circular solar island in Ras Al Khaimah

The Swiss Center for Electronics and Microtechnology (CSEM), in collaboration with the local government of Ras Al Khaimah have established a research center (CSEM-UAE) for testing solar technologies [67]. One of the projected developed at CSEM-UAE is an artificial island floating near the shore in Ras Al Khaimah in the north of the UAE. The project aims to produce electricity and hydrogen using solar power by heating water to produce vapor. It is an artificial island with a diameter of 5 km and a height of 20 m that will have an energy output of 3000 kWh per day and power capacity of 1 MW. It consists of an outer torus and a membrane on which solar panels are placed. The solar panels are always aligned to the sun due to their rotation ability to follow the sun azimuth movement. The island is covered with steel mesh with a pretention of 20 kN in each of the 44 steel cables to ensure the horizontal stability of the surface. The main feature in this installation is its tracking system that uses less power comparatively with conventional trackers. Another advantage is that it has a land availability advantage in areas with limited land availability such in dense cities.

7.10.6. CSEM-UAE innovation center

In addition to the circular solar island, the center has been assisting several local companies with their R&D activities. Among those activities are 3 stand-alone PV systems with a cumulative capacity of 0.1 MW [67]. These installations are being tested to investigate various smart grid solutions.

7.10.7. Masdar Institute

Masdar Institute was established in collaboration with the Massachusetts Institute of Technology as the R&D arm of the Masdar Initiative. It is a graduate level research-driven sustainability-focused university where a lot of research is conducted for supporting the renewable energy sector in the UAE. In fact, the present study has been conducted at the Masdar Institute, and many of the research reported here has been reported by Masdar Institute researchers. The Institute has also acquired one of the largest microelectronics manufacturing facilities to develop new devices relevant to the solar energy sector: solar cells, power converters, etc.

With regard to solar energy research activities, there are several testing facilities. Among those, we mention the research project conducted with the South Korean's Electronics and Telecommunication Research Institute (ETRI). It consists of field-testing of organic photovoltaic (OPV) solar cells in Masdar City. There is also research on the beam-down solar concentrator discussed above, novel solar desalination technologies, solar cooling, etc. There is also research on the policy and economics of solar energy in the UAE, and part of that effort is reported in the present report.

7.11. Projects outside the UAE

Interestingly, the UAE did not act locally only, but it also invested in solar projects abroad, mainly through the Abu Dhabi's Masdar Initiative. The main projects are the first CSP power plant with full storage and the manufacturer of amorphous silicon modules Masdar PV in Erfurt, Germany.

7.11.1. Gemasolar in Spain

Gemasolar is a new commercial solar thermal power plant (CSP) that has been inaugurated in October 2011 in Fuentes, Andalucia, Spain. It was developed by Torresol Energy, a company specializing in developing large CSP plants and it is 40% owned by Masdar. It has 20 MW of production capacity to supply electricity to a population of 27,500 households in the south of Spain and it is expected to produce a net total over 110 GWh per year by operating for 6450 h a year at full capacity. The power plant is expected to save more than 30,000 t of CO_2 emissions per year. The project consists of 2650 collectors spread across 185 ha. Gemasolar is the first commercial solar power plant in the world that uses molten salt thermal storage in a central tower configuration with a heliostat field that focus 90% of the sun's radiation onto its receiver at the center of the tower. Gemasolar can reach an operating temperature of over 500 °C without using oil but directly uses molten salt as a transfer fluid. Therefore, a hotter pressurized steam generated in the turbine which increases the

plant's efficiency due to the high temperatures. The power plant supplies energy to the grid due to its salt storage capacity regardless of the availability of solar radiation.

7.11.2. Valle 1 and Valle 2 in Spain

The two plants which are under-construction in Andalusia in Spain use the cylindrical-parabolic collector technology, each one with 50 MW of rated power and an annual output of 170 GWh. The two plants are also developed by Torresol Energy, a company 40% owned by Masdar.

7.11.3. Sheikh Zayed PV plant in Mauritania

Developed by Masdar, the 15 MW plant started operation in the first quarter of 2013, and it delivers 10% of electricity capacity in Mauritania and is the first utility-scale solar power installation in the country.

7.11.4. Masdar PV in Germany

Masdar PV is a manufacturing plant of thin-film amorphous silicon and micromorph modules [68]. It is 100% owned by Masdar, and aims to be one of the leading manufacturers of thin-film solar modules. It is located in Erfurt, Germany and started production in the third quarter of 2009. Currently, the plant is manufacturing amorphous silicon modules with dimensions of up to 5.7 m^2. More than 35 MW of ground mounted, and more than 5 MW of building-integrated Masdar PV modules have been installed thus far in different regions around the globe.

8. Solar energy industry

Vidican et al. have studied the solar energy industry ecosystem in the UAE [69], and presented it at five levels: actors, institutions, networks, knowledge and technology. With regard to the first level, it included the government, utility companies, Masdar and other companies, financiers, Masdar Institute and other education research and research institutions, and societies and associations such as the Emirates Solar Industry Association (ESIA). With regard to companies, as of 2011, the study suggests that 77 private companies, among which one is active in assembly, four in manufacturing photovoltaic solar panels, mirrors and thermal-collectors, 28 in trading, and 44 in installation and other activities [69].

With regard to manufacturing of photovoltaic solar cells and modules, Microsol International is the only solar cell manufacturer in the UAE and the largest in the Middle East. Microsol International was based first in India and moved to Fujairah, UAE in 2003. It has a manufacturing capacity of 200 MW per annum and it specializes in poly-crystalline and mono-crystalline silicon cells. The company started with a capacity of 15 MW and had expanded to 45 MW in 2006, than to 200 MW and still planning to expand it further. This is to maintain its position as a global player in solar cell manufacturing market. The company currently has a semi-automatic and automatic line built on an area of 5000 m^2 and relies on 2000 people of manpower.

With regard to installers, the largest installer in terms of capacity is Enviromena, which deployed the 10 MW PV power plant in Masdar City, in addition to other rooftop installations in Abu Dhabi city.

With regard to the R&D activities to support the industry, Masdar Institute is currently the only academic institution which focuses on advanced energy and sustainability. Other local universities also contribute to the R&D activities in this area [65].

Here we recall that the UAE is mainly a desert land with abundant sand. Detailed geological and chemical characterization of sand in different regions has shown its high quartz content in some regions [70], which may make it suitable for manufacturing solar-grade silicon. However, we could not track any complete studies on its techno-economic feasibility.

9. Applications

9.1. Power generation

9.1.1. Large PV power plants:

The UAE has a good solar exposure and able to afford high upfront capital costs, two critical factors for the development of large PV power plants to meet the increasing electricity demand. In addition to this, there are several cost and environmental benefits. Harder et al. have examined these economical and environmental benefits associated with building a 10 MW PV power plant in Abu Dhabi [61,72]. The power plant proposed uses 111,111 BP mono-crystalline silicon modules with one-axis tracking spread over an area of 69,980 m^2 near the Abu Dhabi airport. A 5% annual power degradation rate was assumed in order to take into account the degradation in performance of the modules. With regard to the calculation of emissions, it was calculated based on emissions from an existing 1505 MW gas-fired power plant in Abu Dhabi. The installation cost was estimated at USD 9.2/W by assuming a module price of USD 5.05/W (this is around 500% the market cost in 2012). The cost of selling electricity was assumed equal to the cost of electricity from the grid which is USD 0.0816/kWh. The annual energy yield of the plant was estimated at 24.4 GWh, which is around 2.3% of the energy generated from the gas-fired plant in Abu Dhabi. The energy production cost was estimated at USD 0.16/kWh for a lifetime of 30 years which would correspond to a net present value of USD −50.8 million and payback time of 55.4 years. In order to achieve a positive net present value, it is suggested that the installation cost drops by 55% and the cost of selling electricity would have to be USD 0.16/kWh or higher.

It should be noted that the above estimated values did not take into account the benefits of reduced air pollution and GHG emissions. When these were taken into account, the net present value decreased to reach USD 3.5 million. In other terms, for the project to be profitable, the installation cost required would be 3.8% less than the one assumed (USD 8.8/W). This is because the total present value of all air pollution and GHG emissions was estimated at USD 47.4 million.

A sensitivity analysis was conducted, and it was concluded that increasing the selling price of electricity from USD 0.0816/kWh to USD 0.42/kWh would increase the net present value to USD 163.7 million. Also, by keeping the same selling price of USD 0.0816/kWh and reducing the price of the modules from USD 5.05/W to USD 3.7/W (which is around 300 times the market cost in 2011), the net present value would be USD −24.4 million.

Therefore, for making such large power plants economically viable, a minimum feed-in-tariff of USD 0.16/kWh was suggested. Also, registration for the Clean Development Mechanism would significantly improve their economic viability.

From an environmental perspective, it was found that 10,000 t of green house gas (GHG) emissions can be offset annually by producing 24 GWh of clean electricity.

Another motivation for the deployment of solar power plants is the increasing price of oil and decreasing price of solar modules in the international market. Bloomberg New Energy Finance has modeled the economics of a 100 MW PV power plant in the GCC with a installation cost of USD 3.14/W and a lifetime of 25 years [73]. The study suggests that an internal rate of return (IRR) of 9.4% would be achieved if oil prices rise to reach USD 163/bbl by 2030. If the carbon price is included, the IRR would jump to 10.8%. Other scenarios

of oil price increase were studied, and the only one which led to a negative IRR was when the price was USD 50/bbl and no carbon price was included [73].

In this analysis, it is stated that such an economic assessment should be done on the basis of the price of oil in the international market. In other words, PV would not be economic in the near term if the price of oil extraction is considered as the actual price of oil [73]. Also, it was shown that displacing gas instead of oil is less attractive economically because of its lower cost in the international market, and the high efficiency of gas-fired power plants.

Hussain et al. have developed a model to study the economic performance of a large scale 100 MW power plants based on the CdTe single-axis tracking module technology in Abu Dhabi [74]. The model developed has the capability of estimating the sensitivity of the LCOE to the input parameters such as solar radiation, PV module prices, cost of cleaning solar panels, etc. The project was assumed to have a useful life of 25 years, while the CdTe module cost assumed was USD 1/kWh, with a single-axis tracking cost of USD 0.3/kWh. The operation and maintenance costs were estimated at USD 53/kW/yr, among which USD 3/kW/yr is the cost of cleaning the panels. Hussain et al. have estimated a LCOE of USD 0.19/kWh, with an optimistic case of USD 0.17/kWh, and a pessimistic case of USD 0.22/kWh. The study identified the factors that affect the LCOE most as: system degradation rate, solar panel cost, the rate of return on equity, and loan rate. As for the installation cost, an average cost of USD 2/W was estimated, with an optimistic case of USD 1.86/W and pessimist case of USD 2.15/W [74].

A different approach to PV plants is hybridizing them with wind generators as suggested by Mousa et al. [75]. For this purpose, a mathematical optimization model was built to investigate whether this approach is reliable to meet the variable power demand in rural villages in Abu Dhabi for a full year, knowing that both wind and solar energy are inherently intermittent and their intensity varies continuously with time [75]. Interestingly, the authors showed that the availability of these two sources may be considered in a complementary manner to achieve a more stable availability of these two sources: some periods of high solar radiation availability coincide with low wind speeds, and vice versa. The authors found that combining these two sources would require a careful sizing of the wind turbines and solar modules to match the availability of wind and solar energy with demand during a full year. Therefore, the sizing should be very site-specific depending on the availability of these two sources and power demand patterns. For instance, as discussed above, wind speeds reported in different regions in the UAE were different, and the same applies to solar energy as per the solar maps (Figs. 21–26). However, although the objective of meeting demand in a full year could be met, the issue that rose is: during periods of high availability of both energy sources, more power would be generated than demand, and therefore, storage is required [75]. It is worth mentioning that monthly average values of wind speed and solar radiation were used in the model, and that the economics of this approach was not discussed.

9.1.2. Large CSP power plants

In a study published in 2011, Mezher et al. have studied the potential of CSP to meet Abu Dhabi's 7% target (1500 MW) by 2020, contribute to meet local electricity demand, and reduce GHG emissions [76]. This technology was chosen because of a proven record of cost, performance and environmental benefits in desert like areas such as the Mojave Desert in California, USA. From an operation point of view, Mezher et al. pointed that CSP provides a more stable output compared with other generation methods such as PV and wind; and that it has the capability of integrating a demonstrated energy storage technology (thermal storage); and that it enables operating both power generation and water desalination in a cogeneration setup.

Based on the forecasted electricity demand in the timeframe 2011–2030, several scenarios were investigated for the deployment of CSP plants at large scale. Data used in all scenarios was based on the Shams 1 power plant, and it was assumed that all plants have thermal storage capacity to enable 4400 h per year [76].

This study suggests that, when CSP plants are deployed instead of gas-powered plants, the CO_2 emission reduction will be around 398 g/kWh, and that CSP can theoretically meet the 7% target by 2020, and play an essential role in meeting electricity demand in Abu Dhabi beyond 2020. However, that would be associated with several challenges which need to be addressed first. For instance, renewable energy is new to the UAE market, and that puts it in a competitiveness disadvantage [76]. Also, the workforce, institutions, and the infrastructure may not be ready to handle this change. Therefore, a strategy is needed.

The study also suggests that an existing gap between policy expectations and potential of actual performance may hinder the expected benefits from CSP. It was also found that the current plan of Abu Dhabi to deploy CSP may not lead to achieving the 7% target, and therefore, a holistic renewable energy strategy is needed to include other power generation technologies such as PV, biomass, geothermal, etc. The strategy should also include energy efficiency measures, and carbon capture and sequestration. Such a holistic strategy, Mezher et al. suggests, would be achieved with the close collaboration of: scientific and research institutions, business and industry, and the institutions of governance [76].

In 2007, Alnaser et al. have assessed the techno-economic potential of CSP to meet electricity and water demand in the GCC countries. Reportedly, the potential of CSP for power generation in the UAE is 5100–5143 TWh/yr, and for water desalination, it is 538 TWh/yr. It was also predicted that the cost would be USD 0.06/kWh in 2010, to reach USD 0.05/kWh in 2020 [77].

9.1.3. Decentralized building-integrated PV installations

With regard to decentralized power generation, we have mentioned above that 68–76% of electricity is consumed in the residential and commercial sectors, which makes building-integrated PV an attractive option for a wide adoption of solar energy. Radhi has studied the economics of installing PV systems in buildings in different regions in the GCC, including Masdar City [78]. The PV panels were assumed to be integrated in the skin of the building because this offers savings in the construction. 15.2% efficient crystalline silicon modules were assumed to be used. The economical viability of the installation was assessed based on the pay-back time (PBT), net present value (NPV), and internal rate of return (IRR). Radhi reported that a major technical problem is high temperature especially during the summer, because this would cause the efficiency to drop by 5–6% in average. The study also shows, as expected, that tilting the modules at 24° and pointing them towards south leads to a higher yield than putting them horizontally on the roof, while putting them vertically facing south led to the lowest yield [78]. Radhi has shown that integrating PV modules in the skin of the building would reduce electricity consumption by 15–25% because of their thermal insulating properties [78]. The study found that, based on the current price of electricity in Abu Dhabi, the payback time for the nationals which have a special rate (USD 0.013/kWh) would be 270 years, and around 80 years for the non-national who pay a higher rate (USD 0.043/kWh). This is because the system has an installation cost of USD 6/W which results in an electricity production cost of USD 0.0595/kWh during a lifetime of 25 years [78]. The other indicators, which are NPV and IRR, also led to negative values.

However, these figures improved significantly when the price of selling electricity was increased. Based on this analysis, Radhi has suggested two solutions to make building-integrated PV installations economically viable: increasing the electricity tariff, or have the installation cost decrease drastically. From an environment perspective, Radhi stated that 1 m^2 of BIPV would reduce 195 g CO_2/yr [78].

Asghar et al. have also studied the viability of BIPV in the city of Abu Dhabi [59,60]. The study showed that thin-film modules (CIS or CdTe) achieve around 1.13 the yield (kWh/kW) from crystalline silicon modules (pc-Si or mono-Si). With regard to the effect of temperature on performance, the reports that mc-Si and CIS are the most appropriate technologies for the high temperature operating conditions in Abu Dhabi [59,60]. The study also found that the optimal angle should be in the range 20–24°. However, because most buildings in UAE have a horizontal roof, the energy yield at 0° is 93% of that at the optimal angle, while the yield at 90° is 55% of that at the optimal angle. Interestingly, even when the tilt is 90°, the yield is still higher than that obtained from similar modules installed at the optimum tilt in regions with lower solar radiation such as Berlin and Stockholm [59,60].

Asghar et al. have also studied the viability of integrating dye-sensitized solar cells (DSSC) in buildings in Abu Dhabi city. For this purpose, 16 different DSSC cells were placed at a tilt of 24° and tested outdoors for two months (February and March) side-by-side with a pc-Si cell. It was observed that DSSC cells have several advantages and achieve a higher yield than other mainstream PV technologies. During two consecutive 15-day testing periods in March and April, it was shown that DSSC cells have a 28% higher yield than the pc-Si cell. This is because the positive effect of temperature and low irradiance near sunset, sunrise and cloudy periods on the output of DSSC cells. However, the long time stability of the DSSC cells remains the main issue, because all DSSC cells degraded at different rates, and none maintained its performance during the testing period. In fact, some were totally not functional within a 2 months time span [59,60].

Sharples and Radhi have also studied the suitability of BIPV to the GCC society at several levels: environmental operating conditions, cost and environment [79]. To achieve this, a model similar to that proposed by Radhi et al. in [79] was built to simulate a south-facing building with tilted PV panels integrated in it. The study was conducted on several cities in the GCC including Masdar City in Abu Dhabi. Interestingly, the yearly energy output predicted from the PV panels placed horizontally, vertically, and at a tilt of 24° were very close from what Asghar et al. reported [59,60], which validate their models. In this study, it was highlighted again that BIPV reduces cooling demand if the solar panels are placed in a proper manner, and if the solar panels are transparent, they may reduce the indoors lighting requirements. The study also showed that the high temperatures in this region would reduce the performance of the solar panels, which would ultimately affect their yield, and therefore, their economic performance. The authors have also mentioned that the current low and flat rates of electricity affect the attractiveness of BIPV as an alternative source of electricity. In addition to this, electricity rates in the UAE are higher for expats than for UAE nationals, and therefore, BIPV would achieve a higher economic performance for expatriate residents than nationals. In addition to these reasons, the current PV system levels (assumed USD 4.1/kWh) also do not make BIPV competitive with the conventional electricity resources. Therefore, the authors state that BIPV may not be economically suitable (payback time expected is 244–266 years) to end-users in the local residential sector, unless the prices of electricity are revised. This is because local electricity prices are subsidized. When the generation cost of electricity was considered, instead of the end-used price (i.e. without subsidy), the payback time improved to 233–288 years. However, it was found that PV panels would improve the thermal performance of the building and reduce its electricity requirements for cooling by 60–70 kWh/yr for each meter square of PV panels. When this factor was considered, the payback time predicted was 208 years if electricity price remains subsidized, and 45 years if the subsidy is removed [79].

This study has also shown that the economic performance of BIPV varies significantly from one city to the other within the GCC region because of: the electricity prices, weather operating conditions, heat/cooling requirements associated with the weather, and the available amount of solar radiation. For instance, the payback time in Saudi Arabia was 21 years while in Qatar was 80 years when energy savings and actual electricity generation costs were considered. This suggests that the techno-economic performance of BIPV systems in other cities within the GCC may differ significantly from what would be achieved in the UAE's residential sector [79].

Sharples and Radhi have also highlighted that, although BIPV may not be attractive to end-users in the GCC, it may bring several benefits to utilities. Some of these benefits are: savings on the capital cost at the transmission and distribution levels, savings on oil and gas consumption locally can improve income from exports by selling these commodities at the international market price. Also, from an environmental perspective, it was mentioned that installing a one square meter of PV would reduce CO_2 emissions by 195 g per year [79].

In a separate study, Radhi has used a similar model to study the same parameters above in the UAE: Abu Dhabi city and Sharjah city [80]. The study found that because of the high temperatures in these regions, under the standard conditions of irradiance (1000 W/m^2) and the average temperatures in these two regions, the efficiency of the module would drop from 15.2% at room temperature to 10.3% in Sharjah and 9.8% in Abu Dhabi. Also, because the electricity prices are higher in Sharjah (USD 0.04/kWh versus USD 0.013/kWh), and relatively lower average temperatures, the economic performance of BIPV in Sharjah was higher than Abu Dhabi. For instance, a payback time of as little as 6.5 years was estimated in Sharjah and a net present value of USD 600 for each squared meter of installed PV, while in Abu Dhabi, payback times were higher than the lifetime of the installation (higher than 25 years), and net present values were negative. It was shown that the orientation of the panels (horizontal or tilted) may affect the economic performance of the project significantly in both cities [80]. These same parameters were also investigated in another study by the same author, but for different cities (Abu Dhabi, Al Ain, and Dubai), and different energy outputs and different economic performances were achieved [81]. It was also shown that the method of integrating PV in the building affects the thermal performance of the building significantly, and also the economic performance of the project [81]. It was also shown that the location and the way the panels are integrated in the building affect the energy payback time significantly [81].

Differently from the previous study by the same author [79], in this study, it was found that PV panels would improve the thermal performance of the building and reduce its electricity requirements for cooling by 125–145 kWh/yr for each meter square of PV panels (instead of 60–70 kWh/yr). This difference could be due to how the modules are integrated in the skin of the building and the mechanisms of heat transfer that prevail between the building and the surrounding environment.

9.1.4. Solar cooling

Because of the hot climate of the UAE, cooling is an essential commodity in any built environment. For this reason, electricity consumption in the residential sector is high, but we could not find any numbers reported by the authorities or utility companies

on how much electricity is used for this application only [82]. Ali et al. have attempted to answer this question by building a model to estimate the daily electrical cooling load for the residents of Abu Dhabi city (Abu Dhabi island to me more specific), which has an approximate population of 800,000. The authors found that the cooling load corresponds to 40% of the total annual electric load consumed in buildings. It was also found, that on a peak day, 61% of electricity is consumed for cooling. As for the factors governing the day to day cooling requirements, it was found that 59% of the cooling load is due to temperature, 21% to specific humidity, 11% to the direct solar irradiance incident on a horizontal surface, and 8% to the direct solar irradiance incident on a vertical surface [82].

Following those findings, Radhi has studied the effect of temperature on electricity consumption in the residential sector in Al Ain, and it was found that the electric cooling load may increase by up 23.5% in the future if the average air temperate increases by 6 °C as a consequence to global warming [83]. If the current power generation portfolio remains, an increase of 5.4% in CO_2 emissions is expected [83].

To address the high electricity demand for cooling, solar energy could be a viable option. For instance, a 1700 m^2 two-storey building in Masdar City is already being air conditioned by a solar thermal facility of 260 kW. The system uses double-effect absorption chillers that use heat from the sun to activate a chemical process that provides chilled water for cooling.

Al-Alili et al. have also studied the feasibility of a solar powered absorption cycle for air conditioning in Abu Dhabi. A design based on components available in the market was proposed and simulated under the weather conditions in Abu Dhabi for a full year [84]. The 10 kW system uses evacuated tube solar collectors to convert sunlight into thermal energy to run the cooling unit. It was found that this system consumes 47% less electricity compared to a conventional vapor compression air conditioner with a similar size, and it saves 12 t of CO_2 per year. The study also showed that the size and cost of the solar collectors is a critical parameter for improving the economic viability of the installation [84].

Mokhtar et al. have assessed 25 different combinations of solar energy collection and cooling technologies to be operated in the environmental conditions of Abu Dhabi to meet the hourly cooling load during a full year [85]. In order to ensure a full time operation, storage solutions were considered: utility electric grid, hot thermal energy storage, or chilled thermal energy storage depending on the output of the solar collector technology and cooling technology combined. The systems were designed to meet 75% of the entire cooling demand in a full year. The capital cost breakdown indicated that, on average, 73% is attributed to the solar collection part of the system, and that the capital cost determines 85% of the cooling generation cost. Therefore, around 62% (73% × 85%) of the cooling generation cost is attributed to the solar energy collection system. It was found that large size installations are always more economical than small ones. It was also reported that running vapor compression chillers by thin film PV modules or fresnel concentrators are the most economically viable combination: the lowest cooling generation cost was US 0.04/kWh. In addition to this, it is worth noticing that 11 combinations among the 25 achieved a cooling generation cost that is lower than the local electricity prices of USD 0.816/kWh [85].

Another factor that was investigated by Mokhtar et al. is the total efficiency which, according to the author, is an indicator on the land use efficiency of the entire system (not only the solar installation). This factor is primarily important when the cost of land is high or lack of space. It was found that the cooling systems coupled with multi-crystalline PV modules coupled with compressor vapor chillers achieved the highest efficiency of 32%. A sensitivity analysis was conducted, and it was reported that the lower the efficiency, the higher the influence of the cost of land on the cooling generation cost. It was also reported that a critical parameter in selecting the optimal technologies and designing the system is the time distribution of solar radiation (both DNI and GHI) and cooling demand [85]. Ideally, we would like cooling demand to be in phase with solar irradiation, but in reality, this is not the case, therefore, technological solutions are needed to match the supply side (i.e. solar collection) with the demand side (i.e. cooling), at all times. Another conclusion is that the optimal technology is rather location specific and application specific (a cooling load in offices or in a residential compound are different). The authors have also pointed a reliability issue because some equipment used for refrigeration are not designed for such hot climates [85].

Otanicar et al. have also reviewed and compared different solar cooling technologies, and their conclusion was that PV driven processes have a higher efficiency compared with thermally driven processes. Also, PV driven have a higher cost reduction potential because of the falling cost of PV modules. In addition to this, it was found that PV driven processes have a lower environmental impact in terms of CO_2 emissions [86].

9.2. Hydrogen production

In 2001, Kazim and Veziroglu have proposed a solar hydrogen generation system for the UAE to bridge the gap between oil and natural gas demand in the period from 2000 until 2100 [87]. Their hypothesis was that the UAE would fail to meet its share in the oil market by 2015 and in the natural gas market by 2042. The variables considered in their analysis were: (1) population growth which was assumed to increase from 2.9 million in 2000 at a constant growth rate of 2% per year, (2) energy demand which depends on the population growth and another factor for taking the life-style improvement into account, (3) the gross national product which depends on population growth, energy demand, and another factor to take technological development into account, (4) hydrogen production which depends on the difference between the energy produced from fossil fuels and the UAE's share in the world energy market, (5) the cumulative area of solar cells required to produce the desired amount of hydrogen, which depends on the efficiency of the electrolysis device, the efficiency of the solar cell, and the solar insolation, and (6) the total income from fossil fuels (oil and natural gas) and hydrogen. They suggested that hydrogen production should commence in 2020 with an energy production of 10^9 GJ/yr to reach 7.8×10^9 GJ/yr in 2040, 20×10^9 GJ/yr by 2060 and 40×10^9 GJ/yr by 2080. The authors predicted that hydrogen would contribute by 20% to the total income by 2020, 50% by 2042, and 90% by 2100. With regard to the photovoltaic solar cell area to meet the 2020 and 2040 targets, 1000 km^2 and 6000 km^2 would be required by assuming the solar cells are 18% efficient. After 2080, the land required to install the system would be around 33% of the UAE's land, and to solve this, collaboration with neighboring countries such as Qatar, Oman and Saudi Arabia is recommended [87].

Although the current population and energy consumption rates are higher than what Kazim and Veziroglu assumed [87], which affects their predictions significantly, the reasoning behind their approach for establishing such a large solar hydrogen generation system to help the UAE maintain its share in the energy market and diversify its economy remains valid.

In another study published in 2003 by the same authors [83], it was suggested that proton exchange membrane (PEM) fuel cells could be introduced to generate 1% of the UAE's total electrical energy in 2010. It was also suggested that electricity produced from PEM fuel cells could be gradually increased to account for 90% of the total electricity production by 2100. This can be

achieved at a growth rate of 7% per year. The study forecasted significant economic and environmental benefits to result from the implementation of this proposal. From an economic point of view, USD 24,000 billion of fossil fuels could be saved in the period of 100 years, which is around 500 times the 2000s gross national product. From an environmental point of view, 1.4×10^{15} MJ/yr of fossil fuel based electrical energy would be saved for the same period of time. Although it is clearly stated from where hydrogen can be obtained to feed the fuel cells, the solar hydrogen system proposed by the same authors could be used [88].

Although the rate of energy generation and cost variation during the period of 100 years may not be accurate because they do not agree with the current figures, the reasoning remains valid, and the environmental and economical benefits remain correct, at least qualitatively.

As for the method for generating hydrogen from solar energy, Mokri and Emziane have conducted a feasibility study on the use of a hybrid solar concentrating system which is based on converting sunlight into both heat and electricity to achieve a high generation efficiency. The operation of the system is based on boiling water, which reduces the electric energy requirements for powering the electrolysis device. By considering the DNI values recorded in Abu Dhabi, a modeling investigation showed that the system could achieve 22% efficiency, which is around 2–3 times the widely used alkaline electrolysis technique [89].

A comprehensive comparison between the different hydrogen production methods which can be used in the UAE is provided in [90]. The methods covered are based on fossil fuels (coal, crude oil, and natural gas), nuclear energy and renewable energy (solar, wind, biomass, geothermal, wave, tidal and ocean thermal energy). The study mentions that producing hydrogen by using electrolysis devices which are powered by photovoltaic solar modules consumes more land than the other production methods. It also shows that its cost is around twice that of natural gas, higher than that of biomass but it less than that of wind.

9.3. Transportation

Masdar City has now its own electric cars infrastructure which consists of 13 conventional electric vehicles and another 9 self-driving electric vehicles, all powered by solar energy generated in the city. While the self-driving ones circulate inside the city only, the conventional ones move around Abu Dhabi city and its surroundings in the context of a pilot project which aims at building a larger infrastructure of electric vehicles in Abu Dhabi [91].

This transportation infrastructure can be used for energy storage in the city when the solar installations are generating less power than required. More specifically, the aim of one study was to make the Masdar Institute campus in the city energy-independent by putting the extra energy generated by its rooftop solar installation in the batteries of the electric vehicles and take it back when needed [91]. For this purpose, the authors tried to follow the vehicle-to-grid (V2G) approach. A model which considers energy production by the solar installation and energy consumption in the campus was built, and the results suggested that up to 7 h of storage time can be provided by using the existing vehicles.

In 2003, Kazim has suggested the replacement of 10% of all internal combustion vehicles in the UAE by fuel cell vehicles in 2005, and keep introducing more of them until all internal combustion vehicles are displaced from the roads by 2025 [88]. In this study, Kazim stated that the annual growth rate of demand for internal combustion vehicles was 6%, and that the company BMW had forecasted that up to 30% of vehicles in the UAE roads would be powered by hydrogen by 2020–2030. Kazim assumed an average driving distance of 29,000 km/yr, and the ratio of number of vehicles per capita to decrease from six people per vehicle in 2000 to two people per vehicle in 2025, and a population grown from 3 million in 2000 to 4.5 million in 2025. These assumptions led to predicting that 780,000 fuel cell vehicles would be needed in 2005, and this number would grow at 17.8% per year, which is three times the growth rate of internal combustion vehicles, to achieve a 50% share by 2020 and 100% share by 2025. From an environmental point of view, 14.4×10^8 kg of polluting gases would be saved during the 20 years, and this corresponds to USD 230 billion of financial saving. The same study suggested that the annual cost of fuel cell vehicles is USD 180 less than internal combustion vehicles [88].

Based on the current figures of population growths, Kazim's model underestimates this parameter, and this means that the economic and environmental benefits predicted might be underestimated.

9.4. Water desalination

The UAE climate does not allow high rainfall rates, which are in the range of 110 mm in average, but vary from year to year, and also from location to location [91]. Rainfall records from 1975 till 2005 show the following average rates: 72.07 mm (Abu Dhabi), 96.02 mm (Dubai), 60.98 (Al Ain), 103.42 mm (Fujairah), 108.94 mm (Sharjah), 101.59 mm (Ras Al Khaimah). These records also show a wide variation from year to year [92]. For instance, in the years 1997 and 1998, the rainfall rate was around 200 mm, while in the years 1999, 2000 and 2001, the rate was around

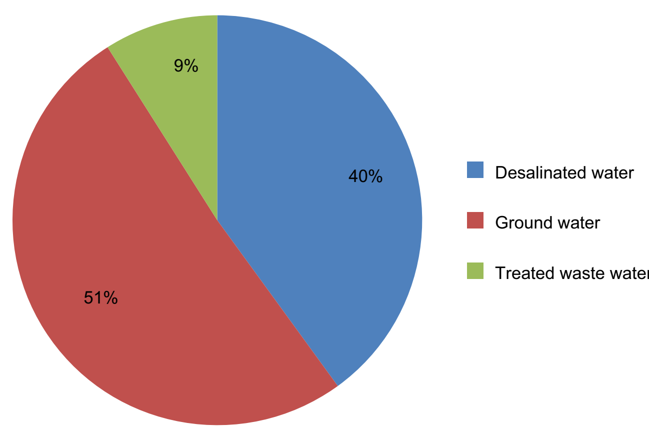

Fig. 41. Water resources in the United Arab Emirates [94].

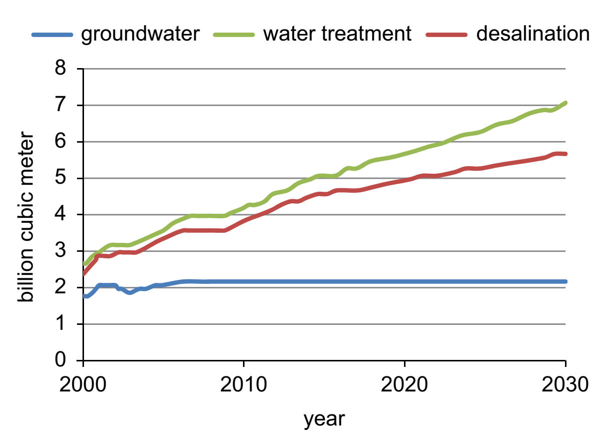

Fig. 42. History and forecast of water resources in the United Arab Emirates [94].

50 mm or less [87]. As a result to these moderate rainfall rates, the UAE has the third lowest amount of renewable water resources (run off, springs, etc.) per capita in the world (19.01 m^3/capita in 2011), with a total renewable water source of 0.15 billion cubic meters [93]. Therefore, the main sources of water remain ground water, sea desalinated water, and treated waste water to meet the yearly demand which is around 4.5 billion m^3 [94]. This explains why the UAE has 14% of the world water desalination capacity which makes it second on the list of countries who rely on desalination as a primary source of fresh water [95]. Desalinated water production capacity in the country has been increasing by 6% per year between 2006 and 2011 to meet around 40% of the total demand and reach 7 MCM/day in 2011 (see Figs. 41 and 42) [96]. This share is expected to increase because of the effect of climate change on reducing rainfall levels, and therefore, ground water availability, in addition to the increasing irrigation requirements. This share is also expected to increase because of the rapid population growth and industrial activity [96]. Here we should recall that desalinated water supplies around 90% of the demand in the domestic sector, and that ground water supplies around 96% of the demand in the agricultural sector. Therefore, demand for desalinated seawater is driven by the rapid population growth and economic growth (i.e. industrial activities) [94].

In addition to the above, it has been documented that salinity of ground water has been increasing because of seawater intrusion and over extraction [97]. Sherif et al. reported that saltwater intrusion from the Gulf of Oman has become the leading factor of water salinity in the UAE's eastern aquifer especially near the coast, which was not the case prior to the year 2000. It was found that seawater intrusion extended about 8 km inland from the coast of the Gulf of Oman [96].

Furthermore, even in areas far from the sea, such as Al-Ain, the quality of ground water has been deteriorating as high levels of Fe and Zn were detected. The investigators stated that these could be attributed to the sewage effluent, industrial waste, and plants surrounding the wells. This may suggest again that more water desalination is needed [98].

Mezher et al. have compared the different desalination technologies in terms of their energy requirements, water production cost, environmental impact and their potential technological improvements, and they have also provided an analysis on the situation of water desalination in the UAE [95]. Their study suggests that 63% of desalinated water is produced by using the multi-stage flash technology (MSF), 12% by using membrane reverse osmosis (RO), 6% by using multiple-effect distillation (MED), and the remaining 19% is based on other technologies, with natural gas being the typical source of energy for running these processes [95]. It is worth mentioning that MSF and MED processes require both heat and electricity, while RO requires electricity only, and that these processes can be hybridized (operated in parallel) which is the case in some large plants in the UAE. In order to improve the environmental impact of these plants, the authors provided several recommendations, among which is the utilization of solar energy for running these processes. As a matter of fact, Afgan [99] has conducted a sustainability analysis on four desalination scenarios in the GCC: MSF for water desalination only, MSF for water desalination and power generation which is the dominant process in the UAE, RO, and RO powered by PV. It was shown that this last scenario is the most sustainable in terms of its environmental impact.

Trieb et al. have also suggested that harvesting solar energy in large CSP plants to drive desalination plants would play a significant role in meeting water demand in the UAE [100]. According to the authors, the main motivation behind such an approach is that CSP has a higher cost reduction potential than conventional fuels, especially in regions with abundant seawater resources and solar radiation. Trieb et al. have built a model to assess the potential of such an approach, and they reported that UAE could produce 50 MCM of CSP-driven desalinated water by 2010 (less than 1% of the projected demand), 900 MCM by 2020 (11% from the projected demand) to reach 9370 by 2050 (84% from the projected demand) [100].

However, as Jijakli et al. suggest, solar driven desalination is not necessarily more environment friendly than conventional methods [101]. Jijakli et al. have studied the environmental impact of several options for supplying fresh water (1250 l/day) to remote areas in the UAE: solar still for desalinating ground water, PV-RO for desalinating ground water, or water transported by truck from a central gas powered seawater RO plant [101]. A life cycle analysis (LCA) has shown that RO-PV has the lowest environmental impact, and the solar still has the highest. This means that conventional processes such as transporting water from conventional RO plants to remote areas by truck maybe more environmentally friendly than solar driven processes in some circumstances. This is because the environmental benefits of using solar energy could be offset if the materials used in making the system and the manufacturing process are not selected wisely. This is because materials and the manufacturing process may involve intensive GHG emissions, water usage, chemical waste, radiation, etc. [101].

Below, we discuss the potential of solar energy to drive the different desalination technologies:

9.4.1. Multi-stage flash desalination (MSF)

MSF is currently the dominant desalination process in the UAE because of the relative inexpensiveness of energy (i.e. natural gas), reliability, large capacity requirement and cogeneration of both fresh water and electric power. In fact, large MSF plants in the UAE are typically co-generation plants.

MSF co-generation plants use natural gas. Ali et al. have reviewed the techno-economical aspects of powering desalination plants by using solar energy [102]. Ali et al. showed that solar thermal collectors have been usually used for running MSF processes in 11 different installations around the world like in Safat (Kuwait), El Paso (USA), etc. The study showed that PV panels have also been used like in Gaza (Palestine). The cost of water from solar-driven MSF installations was found to be in the range USD 1–5/m^3. Based on the UAE Ministry of Energy's annual report for electricity and water, the end-user price of water is in the range USD 0.7–3.6/m^3, which shows that solar-driven MSF installations can be an economically viable option especially at large capacities.

9.4.2. Multiple-effect desalination (MED)

In 1984, an MED plant powered by flat plate solar collectors was installed in Abu Dhabi [103,104]. The plant has a capacity of 80 m^3/day and a specific energy consumption of 50 kWh/m^3, which is typical for an MED plant. The cost of water production was estimated at USD 7–10/m^3. This plant has stopped operation.

9.4.3. Reverse osmosis desalination (RO)

Ali et al. have listed 45 solar powered RO plants around the world, and it was noticed that 36 of them use PV panels to generate electricity and convert it into mechanical power in order to inject water through the membrane [105]. Two of the installations use a hybrid energy supply of PV–wind–diesel and four use PV–wind, and the rest use solar thermal collectors hybridized with heat engines. None of these is installed in the UAE. The largest capacity among the 36 installations which use PV only as an energy source is 53 m^3/day, and the specific energy consumption is in the range 0.89–32.4 kWh/m^3, and the lowest water production cost was USD 3.25/m^3 [102]. With regard to the installations with hybrid energy supply (PV–wind and PV–wind–diesel),

the largest capacity is 300 m^3/day which is based on PV–wind–diesel as an energy source, and the specific energy consumption is in the range 3.3–16.5 kWh/m^3, and the lowest water production cost is USD 3/m^3. With regard to installations which is solar thermal collectors with heat engines to drive the RO process, the largest capacity is 54 m^3/day, and the specific energy consumption is in the range 2–3 kWh/m^3, and the cost of water production was reported on only one installation and it was USD 15/kWh [102].

Helal et al. have studied the economic feasibility of an RO installation powered by PV modules in remote areas in the UAE [105]. Three configurations representing different sources of energy were studied: diesel, hybrid diesel–PV or PV only. The desalination capacity of the hybrid and diesel systems is 20 m^3/day each, while the capacity of the system powered by PV only is 44 m^3/day with 20 m^3 being generated during sunshine hours. Helal et al. have included the emission-related costs in their analysis [105]. The results suggest that the diesel, hybrid and PV powered installations produce water at USD 7.64/m^3, USD 7.21/m^3 and USD 7.34/m^3, respectively. However, because of the falling cost of solar panels, it was estimated that water can be produced at around USD 6.1/m^3 by the PV powered installation if the cost of solar panels reach USD 1/W (which is the market cost of solar panels since 2011). Based on the same analysis, it was shown that hybrid installation would benefit less from the falling cost of solar panels. It was estimated that water can be produced at around USD 6.5/m^3 by the hybrid installation if the cost of solar panels reach USD 1/W [105].

In another study, Helal et al. have reported that the cost of water from a 100 m^3/day seawater PV-RO unit connected to the electric grid is USD 3.7/m^3. This was 51% of the cost from a PV-MVC unit with a similar size and operated under similar conditions (USD 7.3/m^3) [105,106].

Lamei et al. have studied the effect of the price of PV modules in the market, on the cost of water production in the MENA region. It was found that, for a cost of electricity in the local market of USD 0.09/kWh (slightly higher than in Abu Dhabi, USD 0.0816/kWh), PV-RO may become competitive only if the cost of PV systems falls below USD 2/W [107].

9.4.4. Mechanical vapor compression desalination (MVC)

Helal and Al-Malek have proposed a detailed design for an MVC system powered by solar panels and a diesel generator for remote areas in the UAE, with a desalination capacity of 120 m^3/day [106]. The role of the diesel generator is to maintain a continuous production because electric batteries may not be a practical solution for storing electric energy from the solar panels. The unit is designed to supply both desalinated seawater and electric power in remote areas. Although the cost of producing water was not reported, it was shown that 179 t of CO_2 would be avoided yearly [106].

In another study, Helal et al. have designed two 100 m^3/day seawater desalination systems for remote areas in the UAE: PV-MVC and PV-RO units both connected to the electric grid to achieve continuous operation. It was shown that the water cost from the PV-RO (USD 3.7/m^3) is 51% of the cost from the PV-MVC (USD 7.3/m^3) [105,106].

9.4.5. Other desalination technologies

Solar collectors, solar ponds or PV panels can be used to provide thermal and/or electrical energy to run the conventional desalination processes discussed above. In addition to those, there are other desalination technologies and modified designs of conventional desalination processes that run on solar energy: solar stills, humidification–dehumidification, etc. Those have been reviewed in fair detail by Li et al. [108]. The cost of water from those installations with a capacity above 20 m^3/day are shown in Fig. 43. We chose this minimum capacity so we can include Helal's design of the PV-RO system designed for the UAE conditions. It is worth mentioning that some of the costs included in figure are obtained by modeling. In fact, costs reported on large capacity plants are all obtained by modeling because there are no

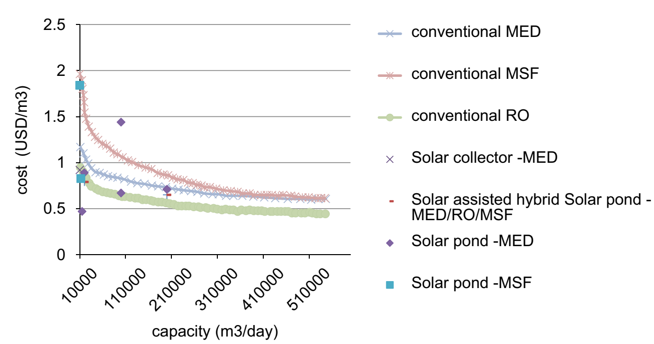

Fig. 44. Cost comparison between conventional desalination technologies and solar-driven desalination technologies [108,109].

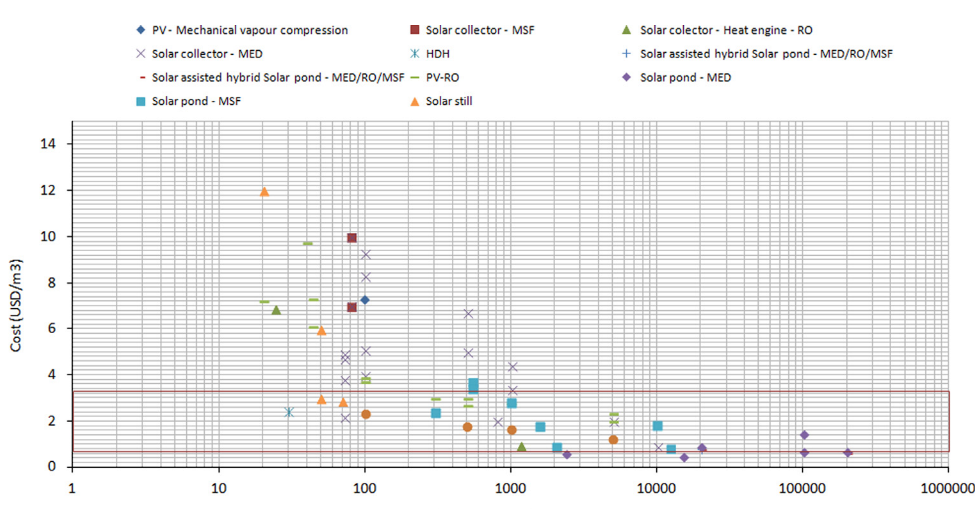

Fig. 43. Cost of different solar driven desalination processes (the area in red shows the end-user price of water in the UAE, some of the data points are obtained from [108]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

large solar desalination plants in the world yet. We include those modeled large capacity installations to show the economic potential of solar desalination in the UAE. From Fig. 43, we conclude that, to gain the economic benefits of solar desalination, large capacities are needed. In addition to this, and as suggested by Helal et al. [105,106], because of the falling cost of PV modules, processes that run on PV (i.e. RO and MVC) have a higher cost potential than processes that run on thermal energy.

Wittholz et al. have built a cost database of more than 300 operating desalination plants around the world. We have used those findings to compare the cost of desalination from conventional technologies with the cost of solar desalination obtained by modeling in several studies [109] (Fig. 44).

Here, it is worth mentioning that the advantage of solar energy over wind energy, which is available in the UAE, is that it can be used to run both thermal (MSF, MED, etc.) and electrical (RO, MVC, etc.) processes alike, or hybrid [110]. This flexibility may guarantee some economic and performance benefits. With regard to the cost of these solar processes, because of the rapid falling cost of PV modules in the market, the electric driven processes (RO, MVC, etc.) may benefit from this advantage more than their thermal counterparts [107].

9.5. Street lighting

In addition to the applications above, street lighting is being used in some locations in the UAE. For example, all street lighting in Masdar City in Abu Dhabi is produced from solar panels mounted on the pole itself and equipped with battery storage. Abdul Hadi et al. have estimated 117,000 high intensity street lighting poles in the city of Abu Dhabi, so they conducted a life cycle analysis (LCA) to determine the environmental impact of various street lighting methods over a lifetime of 14 years [111]: (1) stand-alone PV powered LED street lighting with battery recycling at 80%, (2) stand-alone PV powered LED street lighting without battery recycling, (3) grid connected LED street lighting, (4) stand-alone PV powered CMH (Ceramic Metal Halid) street lighting with battery recycling, (5) stand-alone PV powered CMH (Ceramic Metal Halid) street lighting without battery recycling, and (6) grid connected CMH (Ceramic Metal Halid) street lighting. It was found that CMH consume far more energy than LED, and therefore, it has a higher environmental impact when operated in the same conditions. It was also found that recyclability of the batteries overweighs the impact of using electricity from the grid. Among all options, the least environmental impact would be achieved when stand-alone PV powered LED street lighting with battery recycling is used [111]. However, in these LCA analyses, the energy and water consumption associated with cleaning the solar panels when they get dusty was not considered in the model.

10. Policy options and financing schemes

Ferroukhi et al. have studied the drivers and barriers of the GCC renewable energy market, and they emphasized that the current heavily subsidized rapidly growing energy consumption is reducing oil and gas exports and revenues [65]. Therefore, in order to enhance revenues and preserve these fuels for the long-term, transition towards alternative sources of energy is required. It seems that the UAE is already moving ahead in this direction according to the initiatives and projects discussed above. According to Ferroukhi et al. there are several other reasons which are already driving this transition: growing local energy demand, increasing commitment to reduce energy subsidies, depleting resources, environmental concerns, abundant solar resources, and the already set renewable energy targets.

However, Ferroukhi et al. have also acknowledged barriers of three natures: market and technological, policy framework and legislation, and financial. With regard to market and technological barriers, they include the short experience in this field because a solar industry does not exist until few years ago only, and inherent technological limitations such as intermittency of solar radiation and need for storage for a full time operation. With regard to policy and legislation barriers, they include the lack of a legal policy framework for the promotion of renewable energy in general, and solar energy in particular. Such a framework would attract investors and developers to the local market. According to Ferroukhi et al. there are two factors that may delay the establishment of such a framework: first, not all entities benefit from solar energy because there are many entities which benefit from the current scenario of energy supply; and second, accessibility to the grid. With regard to the third category of barriers (financial), it includes the high capital required for implementing solar energy projects at large scale, and the lack of a financing mechanism to make solar energy competitive with other sources of energy. As a matter of fact, the average retail price of gasoline and diesel is among the lowest worldwide. The authors recognize that that resource availability and technico-economics are not major barriers to large deployment of solar.

Therefore, in order to tackle those barriers, Ferroukhi et al. suggest the promotion of favorable policy frameworks with a long-term commitment. Such frameworks should encourage incentives for R&D institutions to produce knowledge and expertise. Such frameworks should also encourage private investments in this sector. In addition to this, the pricing mechanism of conventional fuels should be consolidated to consider their environmental impact. Also, there has to be efforts through the media and/or financial incentives to encourage the end-users adopt more sustainable sources of energy.

Sgouridis et al. have developed a model to study this impact of a more sustainable energy strategy on carbon dioxide emissions and financial costs of the energy system in the UAE [112]. Three strategies with different levels of commitment were studied within the time-frames 2012–2020 and 2012–2030, and discussed [112].

Mezher et al. have reviewed the policies implemented in 61 countries for meeting their renewable energy targets [113]. Based on the review, Mezher et al. attempted to propose financing practices for Abu Dhabi to achieve its target of having 7% of its power generation capacity based on renewable energy by 2020. According to Mezher et al. policies can be grouped in six categories: (1) feed-in tariffs (FITs) which is based on having the utility company purchase electricity generated from renewable energy generators at a fixed price, (2) Quotas which can also be called Renewable Portfolio Standard (RPS), Renewable Obligation (RO) or Mandatory Market Share (MMS) policy, and they are all based on meeting a predetermined target which is usually a percentage of the country's total generation capacity before a specific point in time, (3) Centralized Bidding or Tendering, which is based on calling for bids from investors to install a certain capacity at the lowest possible cost, (4) Investment Tax Credits which is based on lowering the installation cost through compensation, (5) Subsidies or Rebates and they are based on subsidizing the systems in the market so the consumer sees a lower price, (6) Net Metering which consists in offsetting the amount of electricity obtained from the grid with the power generated from the renewable energy installation and fed into the grid, and this reduces the electricity bill [113].

Mezher et al. argues that the cost of electricity and water are heavily subsidized, and this makes electricity from solar energy in a disadvantage cost-wise. It is mentioned that the cost from the 10 MW plant for instance is around 48 cents per kWh while the residents of Abu Dhabi pay around 25 cents [113]. Based on their

analysis, a mixed policy between Feed-in-Tariffs (FIT) and Quota system are recommended. Although the Abu Dhabi government is reviewing the electricity generation policy with all the actors, Mezher et al. suggest that (1) there has to be a political will in this direction and not be affected by the performance or the cost of the operating systems, (2) the 7% target can be increased in the future, (3) electricity providers buy the electricity generated by solar power system owners and that the power transmission companies provide the grid connection, (4) a trading mechanism between solar energy generators and the utility company needs to be developed, (5) Regulation and Supervisory Bureau (RSB) monitors the market. The study also emphasizes that the price of electricity from conventional sources and renewable energy sources should be reevaluated and take into account the per capita income, and that the energy market should be deregulated for more involvement of the private sectors [113].

With regard to the current low cost of electricity, Reiche has studied the possible renewable energy policies that can be applied in the Gulf countries in general, and suggested that reducing subsidies on electricity is unlikely because it is a way of distributing the national wealth among the citizens [114]. Therefore, according to Reiche, green building codes and standards for fuel consumption of new cars will dominate the energy policy agenda. Reiche also mentions that the UAE has ratified the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol [114]. These can be regarded as drivers for the implementation of effective policies to encourage the adoption of solar energy.

Harder et al. have conducted an analysis on the economic viability of a 10 MW power plant near Abu Dhabi City [71,72]. It was found that the project would have a negative net present value because of the low cost of selling electricity. Therefore, a feed-in-tariff would be required, and this should depend to a large extent on the installation cost (i.e. the cost of the solar modules primarily) and the income associated with reducing GHG emissions.

Radhi has also analyzed the economics of installing building-integrated PV in the different cities in the UAE [78,80,81,83], and it was found that a negative present value would be obtained unless the cost of solar systems decrease drastically, or the price of electricity is increased. No other financing schemes were discussed.

11. Grid integration and operational challenges

The UAE has announced its vision 2030 to become an environmentally, socially and economically sustainable community.

To achieve this goal, Siddiqui et al. call for a smart grid to operate renewable energy distributed generators and manage demand in real time [115]. This is to ensure a sustainable power generation, distribution and consumption across the country. Such an approach would, according to Siddiqui et al. improve the system stability, reduce peak power requirements, improve power quality, and reduce land use (i.e. cost). It was stated that, at 25% of distributed generation, peak demand would be reduced by 15% [115]. Distributed generators may include PV installations, hybrid PV–diesel installations and also fuel cells that may run on solar-generated hydrogen.

Uddin et al. have discussed the suitability of different types of generators to the electric grid in Abu Dhabi [116]. The authors state that TRANSCO (Abu Dhabi's Transmission System Operator) is aware of the distributed generators that will be installed in the future, and work is being to facilitate the integration of these generators in the electric grid [116]. The challenges associated with this integration have been: (1) PV systems can experience several quick variations in the output ($\pm$50% in 30–90 s, and $\pm$70% in 5–10 min); (2) thermal systems can also experience variations in the output but they are more stable than PV generators because of their thermal inertia. It was also found that the integration of wind generators would be more challenging than solar generators because of the higher variability of wind speed and direction.

To overcome this instability issue, Uddin et al. have discussed the technical measures and solutions that are being considered by TRANSCO in order to insure an efficient operation of grid-connected solar generators at all time.

12. Discussion and conclusions

In this study, an overview of the UAE energy sector is provided, and it shows that the UAE supplies 3.8% of oil consumed worldwide and has 5.9% of the world's oil reserve, which is expected to be totally consumed within the next 81 years. It is also worth recalling that the UAE has become a net importer of gas since 2007. The local energy demand has been increasing by 5.2% annually, and electricity demand by 10.8%. Knowing that local electricity generation is based on natural gas, and energy generation is based 35% on oil and 65% on natural gas, the adoption of alternative resources of energy is rather necessary. It was also found that around $\frac{3}{4}$ of electricity is consumed in buildings, among which 40% goes to cooling and air conditioning. Another facet of the situation is that the UAE seeks to diversify its economy, maintain its position in the international energy market, and that their water resources are limited.

The UAE was compared with other countries with similar characteristics, and relatively high energy and electricity consumptions per capita were observed. This has led to the UAE having one of the highest CO_2 emissions per capita worldwide. The main sources of emissions were identified as: electricity and water production, and transportation.

We have shown that wind energy may not be a viable option for wide deployment because of its moderate speeds, and that ongoing nuclear energy programs alone will not meet all the ever increasing energy and electricity demand.

This research also reviews several methods for assessing solar radiation in the UAE, and it was found that their accuracy depends on the location and the solar radiation parameters investigated. We have also shown that southern areas, which are the furthest from the sea and largest population concentrations, are the sunniest.

This study also looked at the local atmospheric conditions, and it was shown that the design of concentrating systems should take the effect of sunshape into account. The effect of dust and temperature on solar modules was also investigated. It was shown that PV technologies with a low sensitivity to temperature increase are the most suitable to the local environment. Methods for tackling the effect of dust were also discussed, namely, self-cleaning coatings and wet cleaning.

Among all PV technologies, we report that organic solar cells have a better performance in the local environmental conditions but their quick degradation remains the main issue.

All solar energy projects and programs were discussed, and an overview of the local solar energy market was provided. Around 135 MW of solar energy production capacity is expected to be operational by the end of 2013, and a similar capacity is either operational or under construction outside the UAE borders. This adds to 40 MW of PV modules installed worldwide, and manufactured by the UAE owned manufacturer Masdar PV. Locally, at least 1600 MW is expected to be operational by 2030.

The usage of solar energy at large scale for electricity production (large PV plants, large CSP plants, and decentralized PV generators), water desalination, hydrogen production, transportation and cooling have been discussed. We showed how different technologies compare, and identified which are most cost effective. The economic and environmental benefits of these applications have also been covered.

From a financial perspective, we found that the cost of electricity from solar power installations is currently higher than electricity from the grid by around the double. However, it is possible to make solar power competitive in the local electricity sector by: (1) introducing a feed-in-tariff, a rebate or any financing mechanism which reduces the cost of the installed system or guarantee an income for the system owner, (2) waiting for the price of solar panels to decrease further, and/or (3) increasing the price of electricity from the grid by removing subsidies.

With regard to electricity generators, it was found that integrating PV in buildings may be more beneficial than large plants because building integrated PV installations improve the thermal performance of buildings and, therefore, reduce their cooling (i.e. electricity) demand, and also reduce transmission losses. In addition to this, we discussed the integration of distributed PV generators in the grid, and we found that work is underway by local authorities to prepare the local electric grid for integrating distributed generators at large scale in the future.

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